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DIGITAL TWINS FOR A CIRCULAR FUTURE

CONFERENCE PROCEEDINGS

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BURGAS FREE UNIVERSITY
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"Digital Twins for a Circular Future"
CONFERENCE PROCEEDINGS BOOK

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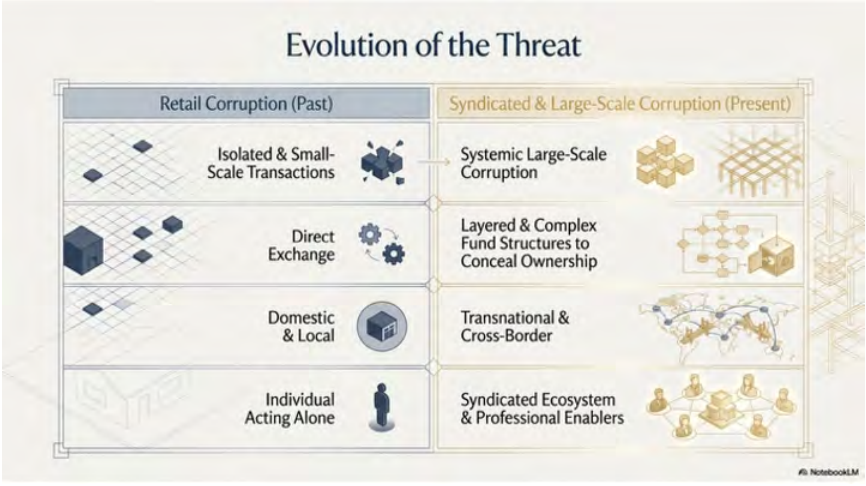
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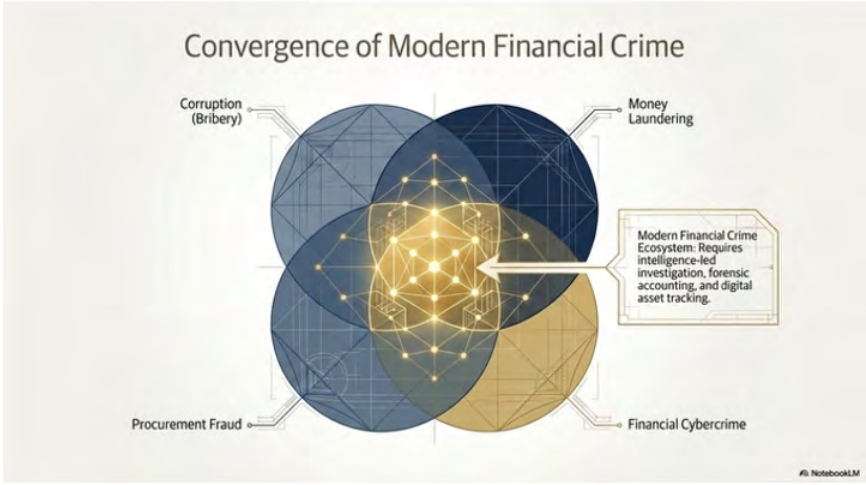
PLENARY SESSION

COMBATING CORRUPTION FOR CIRCULAR FUTURE: MALAYSIAN INITIATIVES

Mr. Mohd Azwan Bin Ramli
Director of the Malaysian Anti-Corruption Agen-cy, Malaysia





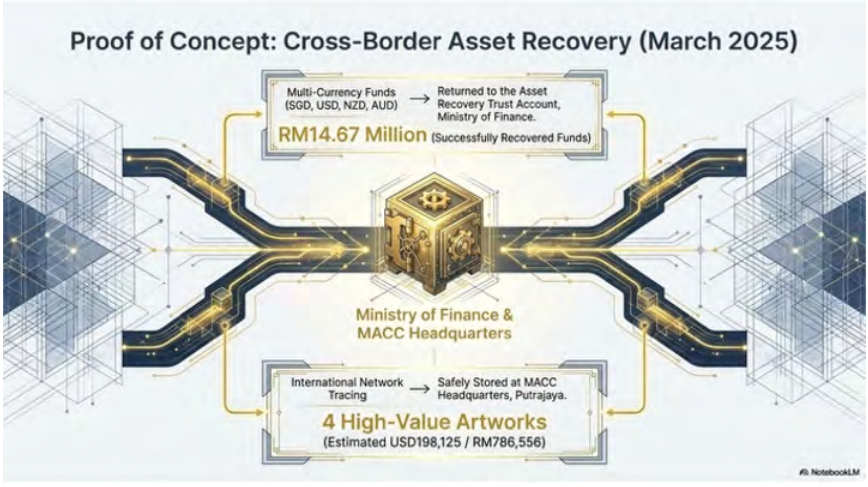

Convergence of Modern Financial Crime
Corruption (Bribery)
Money Laundering
Modern Financial Crime Ecosystem: Requires intelligence-led investigation, forensic accounting, and digital asset tracking.
Procurement Fraud
Financial Cybercrime

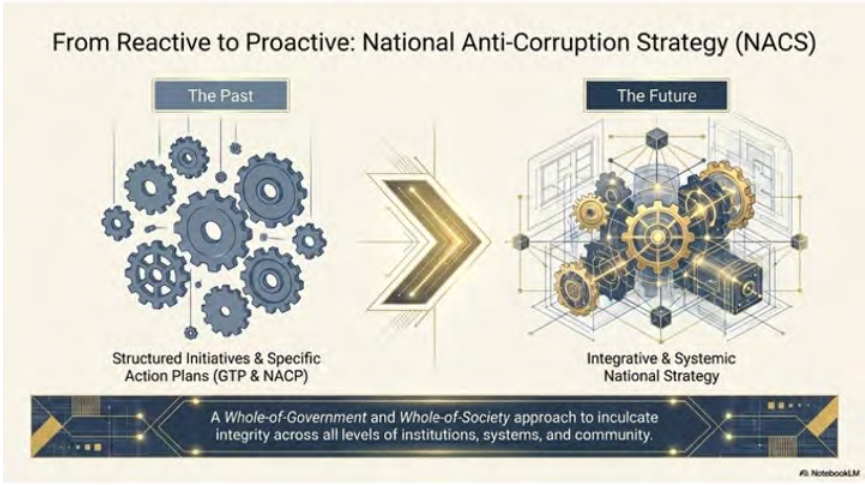

Double-Edged Sword: The Role of Professional Enablers
Large-scale crime does not exist in a vacuum—it relies on experts who legitimize illicit flows, either knowingly or due to weak governance.
Integrity Shield: Due Diligence & Reporting
Illicit Funds
Lawyers, Accountants, Auditors, Corporate Advisors
Formal Economy
Accomplices: Transaction Structuring & Concealment

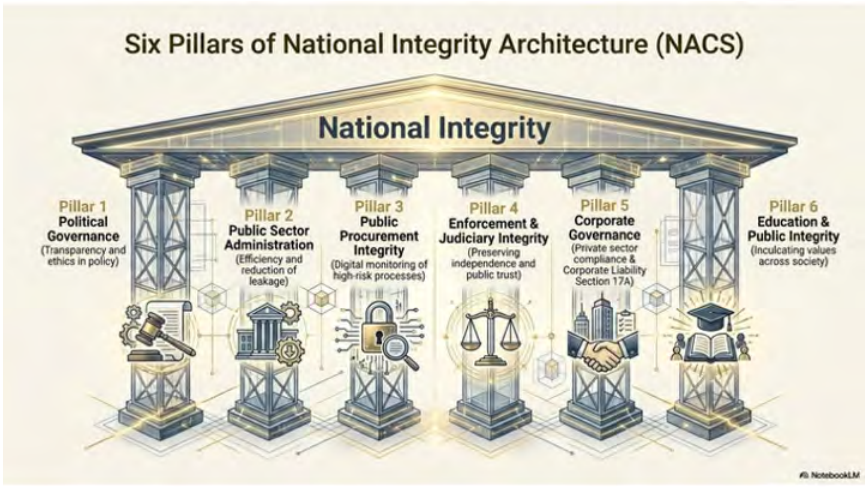

Digital Borders and Virtual Assets
Potential for Anonymity
Cross-Border Digital Banking
High-Speed Virtual Assets
Strategic Response: Requires enforcement agencies to upgrade tools, digital forensic skills, and continuous regulatory cooperation (e.g., Securities Commission Malaysia).


Historical Foundation of Malaysia's Anti-Corruption Ecosystem
2009
Establishment of the Malaysian Anti-Corruption Commission (MACC), in line with UNCAC commitments.
2002
Mutual Assistance in Criminal Matters Act (MACMA) for cross-border investigation support.
2001
AMLATFPUAA enacted, aligning with Financial Action Task Force (FATF) standards.
1960s
Establishment of the ACA Unit under the Prime Minister's Department (Focus on petty corruption).
2002
2001
1960s
NotebookLM

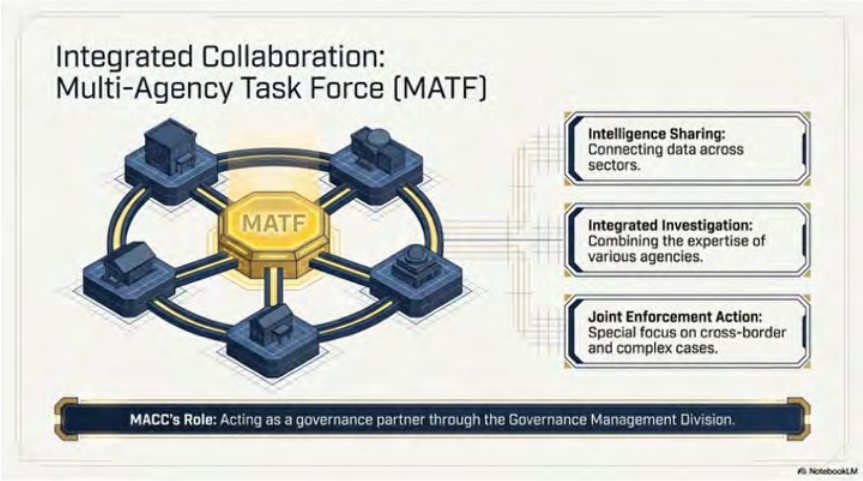

MACC Enforcement Focus in the New Era
Law Enforcement
Directly combating corruption and abuse of power.
Public Procurement Integrity
Plugging leakages in government spending.
Large-Scale Corruption
Targeting high-level and high-profile financial misconduct.
Commitment supported by the recent seizure of illicit assets valued at approximately RM1.29 billion.
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Proof of Concept: Cross-Border Asset Recovery (March 2025)
Multi-Currency Funds (SGD, USD, NZD, AUD)
Returned to the Asset Recovery Trust Account, Ministry of Finance.
RM14.67 Million (Successfully Recovered Funds)
Ministry of Finance & MACC Headquarters
International Network Tracing
Safely Stored at MACC Headquarters, Putrajaya.
4 High-Value Artworks
(Estimated USD198,125 / RM786,556)
NotebookLM

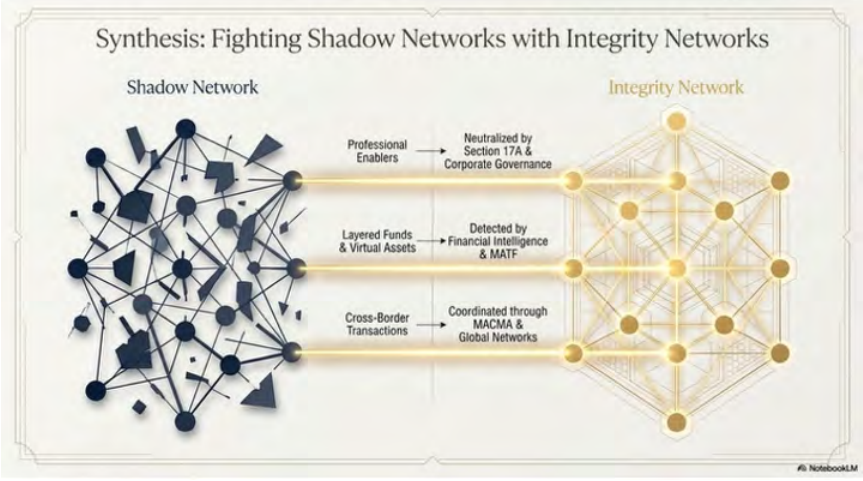

From Reactive to Proactive: National Anti-Corruption Strategy (NACS)
The Past
The Future
Structured Initiatives & Specific Action Plans (GTP & NACP)
Integrative & Systemic National Strategy
A Whole-of-Government and Whole-of-Society approach to inculcate integrity across all levels of institutions, systems, and community.

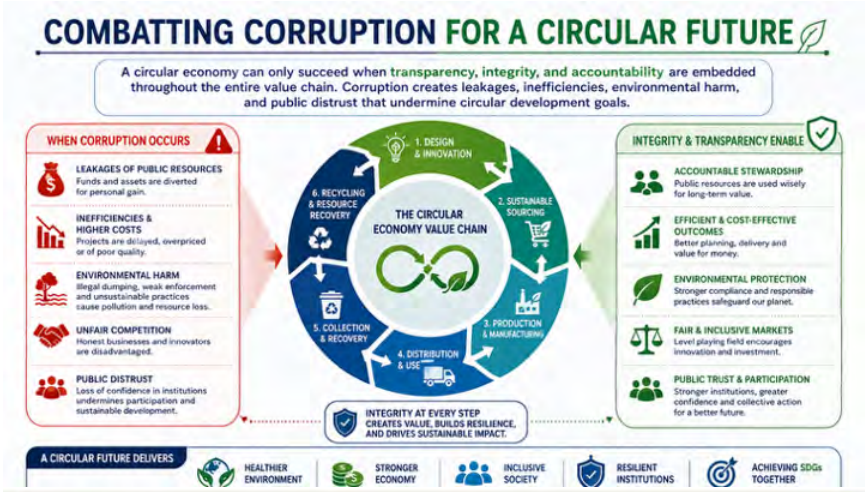

Six Pillars of National Integrity Architecture (NACS)
National Integrity
Pillar 1 Political Governance (Transparency and ethics in policy)
Pillar 2 Public Sector Administration (Efficiency and reduction of leakage)
Pillar 3 Public Procurement Integrity (Digital monitoring of high-risk processes)
Pillar 4 Enforcement & Judiciary Integrity (Preserving independence and public trust)
Pillar 5 Corporate Governance (Private sector compliance & Corporate Liability Section 17A)
Pillar 6 Education & Public Integrity (Inculcating values across society)


First Line of Defense: Early Warning System
Financial Intermediaries. Observation of fund trajectories.
Reporting Institutions. Identification of suspicious transactions.
Informants / Whistleblowers. Early detection of hidden risks.
This financial intelligence ecosystem is the key to breaking the criminal structure before it spreads.


Integrated Collaboration:
Multi-Agency Task Force (MATF)
MATF
Intelligence Sharing:
Connecting data across sectors.
Integrated Investigation:
Combining the expertise of various agencies.
Joint Enforcement Action:
Special focus on cross-border and complex cases.
MACC's Role: Acting as a governance partner through the Governance Management Division.


Building Capacity for Future Threats
Digital Fraud & Complex Financial Manipulation
Trade-Based Money Laundering (TBML)
Concealment of Beneficial Ownership
Collaboration with professional bodies, academic institutions, and financial regulators for research and expertise building.


Synthesis: Fighting Shadow Networks with Integrity Networks
Shadow Network
Integrity Network
Professional Enablers
Neutralized by Section 17A & Corporate Governance
Layered Funds & Virtual Assets
Detected by Financial Intelligence & MATF
Cross-Border Transactions
Coordinated through MACMA & Global Networks


COMBATTING CORRUPTION FOR A CIRCULAR FUTURE
A circular economy can only succeed when transparency, integrity, and accountability are embedded throughout the entire value chain. Corruption creates leakages, inefficiencies, environmental harm, and public distrust that undermine circular development goals.
WHEN CORRUPTION OCCURS
LEAKAGES OF PUBLIC RESOURCES
Funds and assets are diverted for personal gain.
INEFFICIENCIES & HIGHER COSTS
Projects are delayed, overpriced or of poor quality.
ENVIRONMENTAL HARM
Illegal dumping, weak enforcement and unsustainable practices cause pollution and resource loss.
UNFAIR COMPETITION
Honest businesses and innovators are disadvantaged.
PUBLIC DISTRUST
Loss of confidence in institutions undermines participation and sustainable development.
1. DESIGN & INNOVATION
2. SUSTAINABLE SOURCING
3. PRODUCTION & MANUFACTURING
4. DISTRIBUTION & USE
5. COLLECTION & RECOVERY
6. RECYCLING & RESOURCE RECOVERY
THE CIRCULAR ECONOMY VALUE CHAIN
INTEGRITY & TRANSPARENCY ENABLE
ACCOUNTABLE STEWARDSHIP
Public resources are used wisely for long-term value.
EFFICIENT & COST-EFFECTIVE OUTCOMES
Better planning, delivery and value for money.
ENVIRONMENTAL PROTECTION
Stronger compliance and responsible practices safeguard our planet.
FAIR & INCLUSIVE MARKETS
Level playing field encourages innovation and investment.
PUBLIC TRUST & PARTICIPATION
Stronger institutions, greater confidence and collective action for a better future.
INTEGRITY AT EVERY STEP CREATES VALUE, BUILDS RESILIENCE, AND DRIVES SUSTAINABLE IMPACT.
A CIRCULAR FUTURE DELIVERS
HEALTHIER ENVIRONMENT
STRONGER ECONOMY
INCLUSIVE SOCIETY
RESILIENT INSTITUTIONS
ACHIEVING SDGs TOGETHER


Shared Responsibility for Protecting Global Sustainable Development
Key Challenges in APAC:
Networks of money laundering, illicit trade, human trafficking, and transnational crime.
MALAYSIA
Call to Action
Today's corruption relies on global networks to survive; our response must also be global.
International cooperation, information sharing, and Mutual Assistance in Criminal Matters (MACMA) are critical to maintaining integrity.
Collective commitment for shared trust and a common future.
Thank you for listening
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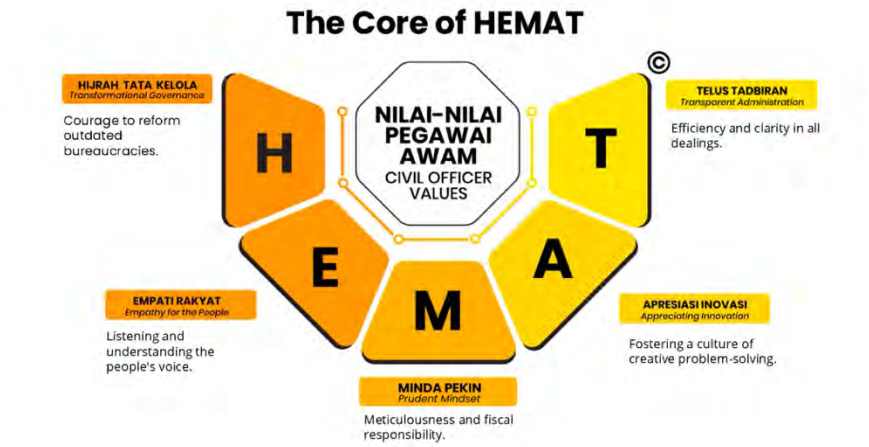
MAINSTREAMING: HEMAT VALUES

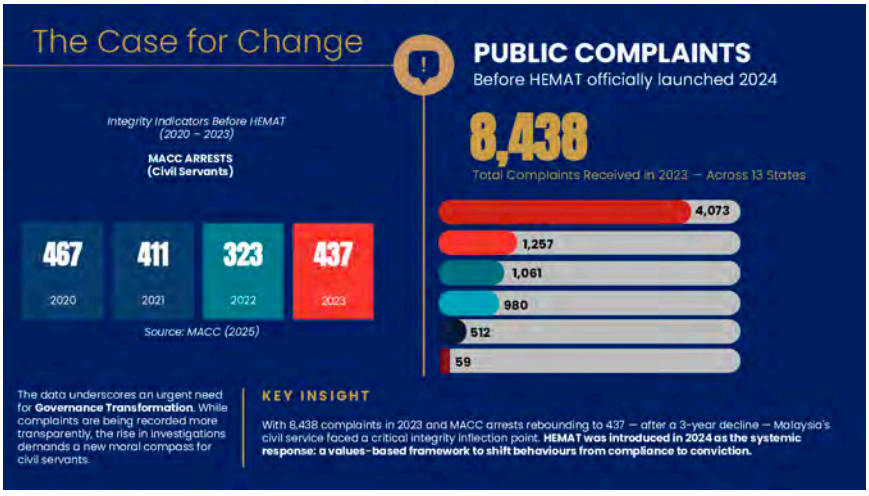
Dr. Norazam Bin Mohd Noor
Special Duty Officer to the Director General of Public Service, Public Service Department, Malaysia






Genesis & Leadership Vision
A Leadership Mandate
Championed by Tan Sri Wan Ahmad Dahlan (DGPS), HEMAT is not a mere slogan but a normative framework to institutionalize excellence.
THE VISIONARY GAME CHANGER
"Change by Command" to "Change by Culture".
NUDGING VS. SHOVING
The core leadership challenge is to move away from coercion and instead design a "choice architecture" where followers wholeheartedly embrace HEMAT values as their own.
INTERNAL GOVERNANCE MECHANISM
Cultivating an ecosystem where moral consciousness and "inner control" serve as the primary compass, fostering self-initiated excellence and intrinsic motivation.
BELIEF IN VALUE-BASED OUTCOMES
Strengthening the conviction that virtuous values inevitably lead to superior results, ensuring that public service reform is sustainable, organic, and deeply rooted.
Strategic Integration: Acts as the operational arm of Malaysia MADANI, aligning with the Public Service Reform Agenda (ARPA) led by the Chief Secretary to the Government
Purpose: To humanize reform and ensure values resonate across every layer of the public sector hierarchy.


The Core of HEMAT
HIJRAH TATA KELOLA
Transformational Governance
Courage to reform outdated bureaucracies.
TELUS TADBIRAN
Transparent Administration
Efficiency and clarity in all dealings.
NILAI-NILAI PEGAWAI AWAM
CIVIL OFFICER VALUES
H
T
E
A
M
EMPATI RAKYAT
Empathy for the People
Listening and understanding the people's voice.
APRESIASI INOVASI
Appreciating Innovation
Fostering a culture of creative problem-solving.
MINDA PEKIN
Prudent Mindset
Meticulousness and fiscal responsibility.


The Case for Change
PUBLIC COMPLAINTS
Before HEMAT officially launched 2024
8,438
Total Complaints Received in 2023 – Across 13 States
4,073
1,257
1,061
980
512
59
Integrity Indicators Before HEMAT (2020 - 2023)
MACC ARRESTS (Civil Servants)
467
2020
411
2021
323
2022
437
2023
Source: MACC (2025)
The data underscores an urgent need for Governance Transformation. While complaints are being recorded more transparently, the rise in investigations demands a new moral compass for civil servants.
KEY INSIGHT
With 8,438 complaints in 2023 and MACC arrests rebounding to 437 – after a 3-year decline – Malaysia's civil service faced a critical integrity inflection point. HEMAT was introduced in 2024 as the systemic response: a values-based framework to shift behaviours from compliance to conviction.

The Case for Change

To materialize the **HEMAT** values into tangible action, Tan Sri DGPS has established three fundamental pillars of a responsive public service. These principles act as the operational engine to ensure that values are not just understood, but felt by the citizens through every interaction.

Operationalizing HEMAT: The Three Pillars of Responsive Service

3 Pillars

1. **FACILITATE**
   Streamlining procedures and removing bureaucratic bottlenecks to make public interactions seamless and effortless.
2. **ACCOMMODATE**
   Adopting a flexible, inclusive, and adaptive approach to meet the diverse and evolving needs of the community.
3. **ACCELERATE**
   Enhancing the velocity of decision-making and delivery to ensure public needs are addressed with the utmost urgency.



Bridge the Gap (Option 2)

To bridge the gap between aspiration and reality, the HEMAT framework is driven by the principles of **Facilitating** ease of access, **Accommodating** diverse citizen needs with flexibility, and **Accelerating** the speed of delivery.

"The 'FAA' approach is the backbone of a responsive public service, turning reform into fast and real-world results."

Nationwide Outreach

'BICARA ASPIRASI' ROADSHOWS

Inclusive Geography: Direct engagement sessions conducted across east and west coast peninsular of Malaysia including Sabah, and Sarawak regions.

The FGD Approach: Utilizing Focus Group Discussions to bridge the gap between Top Management and the Operational level.

Internalization: Shifting from "Command and Control" to a "Dialogue-Based" reform model.



Research Methodology Overview

A comprehensive Mixed-Method study was conducted to evaluate the impact and practice levels of HEMAT values across the service.

Component	Metrics / Method	Focus Area
Quantitative Survey	3,015 Respondents	Internalization across demographics
Focus Group (FGD)	108 Participants	Identifying operational barriers
Indepth Interviews	15 Key Informants	Strategic leadership alignment

Practice Levels Acreoss Values

International Practice Percentage (%)



*Overall Practice Level: **GOOD**. The focus for the next phase is bridging the 40% gap in Innovation and Transformation.

Leadership Commitment : Top Management

LEADING BY EXAMPLE

Data shows significantly higher internalization levels among **Heads of Departments** and **Top Management**.

Their focus remains on strategic transformation, organizational culture, and administrative integrity.



"Leadership commitment is the catalyst for operational success."

Global Footprint & Recognition



Malaysia's Reform as a Global Model

The HEMAT framework has been presented on international stages, including **Indonesia** and **South Korea**.

Positioning Malaysia as a leader in **Value-Based Governance** within ASEAN and beyond.

"Validating local reforms through international benchmarks."

Ecosystem Support and Achievement





THE HEMAT BOOK

A comprehensive guide published by INTAN & CITY University of Malaysia to standardize terminology and expectations.

REAL-TIME DASHBOARD

Data-driven monitoring of agency internalization levels and service metrics.

TRAINING (TOT)

Blended learning modules (online & physical) to certify HEMAT ambassadors nationwide.

The HEMAT Index; Strategic Audit, and Accountability

Quantifying Culture:
Translating intangible moral values into measurable metrics to track internalization levels across all departments.

Diagnostic, Not Punitive:
Serving as a continuous improvement tool. It acts as an operational health check to identify gaps, rather than a mechanism for punishment.

Sustaining the Change:
Functioning as the ultimate accountability mechanism to ensure that reforms are deeply rooted, institutionalized, and resilient over time.

"The HEMAT Index ensures that our core values are not just inspiring aspirations, but audited realities."


TOWARDS A STRATEGIC LEGACY
"HEMAT is the emotional and moral intelligence of our public servants. It ensures that every officer is resilient against time and challenges."
THANK YOU / Q&A
Building a Future-Proof Public Service for Malaysia

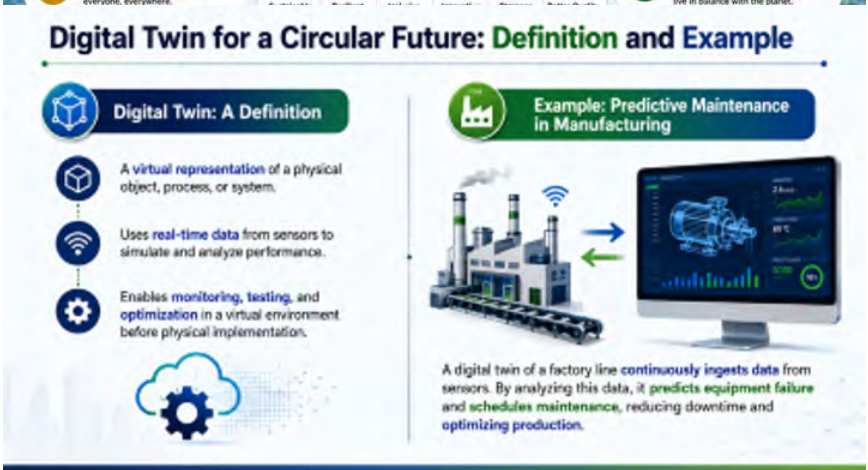
DIGITAL TWINS FOR A CIRCULAR FUTURE: TRANSFORMING GOVERNANCE, SUSTAINABILITY AND INCLUSIVE DEVELOPMENT

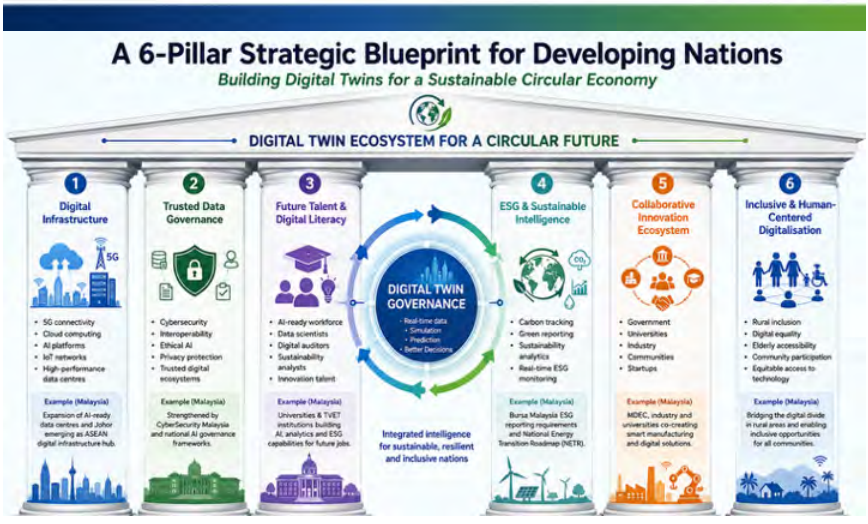
Prof. Dr. Jamaliah Binti Said
Universiti Teknologi MARA, Malaysia






BUILDING A CIRCULAR FUTURE
A future where economies, technologies, governance systems, and societies operate sustainably, intelligently and inclusively.
A CIRCULAR FUTURE INCLUDES
CIRCULAR ECONOMY
Design out waste, keep resources in use, regenerate nature.
AI
Intelligent systems that enhance decision-making and efficiency.
DIGITAL TWINS
Virtual replicas of real-world systems for simulation, prediction and optimisation.
SMART GOVERNANCE
Data-driven, transparent and adaptive governance for better outcomes.
RENEWABLE ENERGY
Clean, sustainable and resilient energy for future generations.
ESG
Environmental, Social and Governance principles for long-term value.
RESILIENT CITIES
Safe, connected and climate-resilient cities for all.
INCLUSIVE DEVELOPMENT
Opportunities and well-being for everyone, everywhere.
CIRCULAR ECONOMY
AI
DIGITAL TWINS
SMART GOVERNANCE
RENEWABLE ENERGY
ESG
RESILIENT CITIES
INCLUSIVE DEVELOPMENT
ONE VISION.
CONNECTED SOLUTIONS.
SUSTAINABLE FUTURE.
THE IMPACT OF A CIRCULAR FUTURE
FOCUS AREAS
FUTURE SUSTAINABILITY
Protect resources, regenerate nature and build a sustainable future.
INTELLIGENT GOVERNANCE
Leverage data, AI and innovation for smarter, transparent decision-making.
SMART CITIES
Connected infrastructure and services that improve quality of life.
CLIMATE RESILIENCE
Prepare, adapt and thrive in the face of climate change.
HUMAN WELL-BEING
Healthy, safe, empowered and inclusive communities.
DIGITAL TRANSFORMATION
Technology and data driving innovation, productivity and impact.
CIRCULAR LIFESTYLES
Make sustainable choices and live in balance with the planet.


Digital Twin for a Circular Future: Definition and Example
Digital Twin: A Definition
A virtual representation of a physical object, process, or system.
Uses real-time data from sensors to simulate and analyze performance.
Enables monitoring, testing, and optimization in a virtual environment before physical implementation.
Example: Predictive Maintenance in Manufacturing
A digital twin of a factory line continuously ingests data from sensors. By analyzing this data, it predicts equipment failure and schedules maintenance, reducing downtime and optimizing production.


A 6-Pillar Strategic Blueprint for Developing Nations
Building Digital Twins for a Sustainable Circular Economy
DIGITAL TWIN ECOSYSTEM FOR A CIRCULAR FUTURE
1 Digital Infrastructure
5G connectivity
Cloud computing
AI platforms
IoT networks
High-performance data centres
Example (Malaysia)
Expansion of AI-ready data centres and Johor emerging as ASEAN digital infrastructure hub.
2 Trusted Data Governance
Cybersecurity
Interoperability
Ethical AI
Privacy protection
Trusted digital ecosystems
Example (Malaysia)
Strengthened by CyberSecurity Malaysia and national AI governance frameworks.
3 Future Talent & Digital Literacy
AI-ready workforce
Data scientists
Digital auditors
Sustainability analysts
Innovation talent
Example (Malaysia)
Universities & TVET institutions building AI, analytics and ESG capabilities for future jobs.
DIGITAL TWIN GOVERNANCE
Real-time data
Simulation
Prediction
Better Decisions
Integrated intelligence for sustainable, resilient and inclusive nations
4 ESG & Sustainable Intelligence
Carbon tracking
Green reporting
Sustainability analytics
Real-time ESG monitoring
Example (Malaysia)
Bursa Malaysia ESG reporting requirements and National Energy Transition Roadmap (NETR).
5 Collaborative Innovation Ecosystem
Government
Universities
Industry
Communities
Startups
Example (Malaysia)
MDEC, industry and universities co-creating smart manufacturing and digital solutions.
6 Inclusive & Human-Centered Digitalisation
Rural inclusion
Digital equality
Elderly accessibility
Community participation
Equitable access to technology
Example (Malaysia)
Bridging the digital divide in rural areas and enabling inclusive opportunities for all communities.


WHY INCLUSIVE DEVELOPMENT MATTERS FOR DIGITAL TWINS
Accurate data. Complete representation. Better decisions for everyone.
1 DIGITAL TWINS DEPEND ON DATA FROM SOCIETY
Digital twins require:
Citizen data
Infrastructure usage
Mobility patterns
Public participation
Behavioural information
IF PARTS OF SOCIETY ARE EXCLUDED
Rural communities
Low-income groups
Elderly populations
Digitally disconnected citizens
Then the digital twin becomes incomplete and biased.
EXAMPLE
A smart city system that only reflects affluent urban users may ignore:
Poor public transport areas
Flood-prone low-income housing
Underserved communities
RESULT
POOR GOVERNANCE DECISIONS
Incomplete and biased data lead to policies and investments that do not address real needs, widen inequality and reduce trust in smart systems.
INCLUSIVE DATA. INCLUSIVE DIGITAL TWINS. INCLUSIVE FUTURES.
A digital twin is only as smart as the society it represents.


1
ABOUT THE PROJECT
Social Inclusiveness Initiative for the B20 Community
Empowering housewives with basic sewing skills to build sustainable income opportunities through a community-based production ecosystem.
Promoting economic resilience
Creating social inclusiveness
Building long-term
2
Connecting participants to grow and succeed
MICROFINANCE INSTITUTIONS
Financial support and empowerment
Access to capital and financial guidance to start and grow their journey.
B20 COMMUNITY PARTICIPANTS (HOUSEWIVES)
EMPOWERED TO GROW & SUCCEED
Quality materials at affordable prices
Reliable supply of quality materials to ensure better products and sustainable production.
SUPPLIERS OF RAW MATERIALS
MYDIN
STRATEGIC MARKET PARTNER – MYDIN
Wide market access through Mydin
Access to Mydin hypermarket chain nationwide – affordable, quality products that reach more customers.

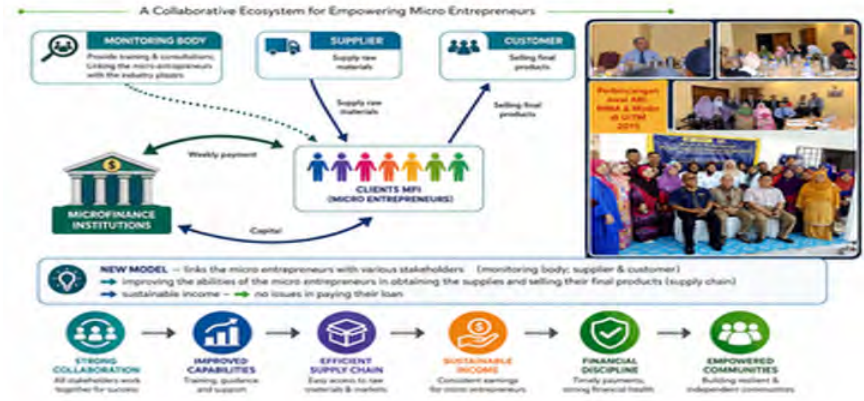

3
PARTICIPANTS & ASSESSMENT PROCESS
Understanding. Assessing. Empowering.
FIRST PHASE
Approximately
30 participants
in the first batch
INTERVIEWS & ASSESSMENTS
Understanding participants' socio-economic background, skills, readiness, aspirations, and challenges.
KEY CHALLENGES BEFORE JOINING
Lack of capital to start a business
Limited marketing and business management skills
Lack of confidence
Limited access to wider markets
Insufficient local demand for their products


4
CAPACITY BUILDING & TRAINING
Building skills. Building confidence. Building futures.
TRAINING FOCUS AREAS
Teamwork & collaborative production
Quality control
Productivity enhancement
Entrepreneurship development
Specialised task allocation
SPECIALISATION-BASED PRODUCTION MODEL
Each participant focuses on specific tasks for higher efficiency and better quality.
CUTTING MATERIALS
SEWING
FINISHING
PACKAGING
QUALITY INSPECTION
THIS APPROACH IMPROVES:
Efficiency
Product Consistency
Productivity
Scalability of Operations
Building Skills
Building Confidence
Building Futures
Empowering participants with skills and knowledge to create sustainable livelihoods and brighter futures.

5
PROJECT IMPACT & OUTCOMES
From skills to income. From dependency to independence.
Technical Competency Improved
Productivity Increased
Self-Confidence Strengthened
Income-Generating Capability Enhanced
PARTICIPANTS ARE NOW ABLE TO:
Produce garments more efficiently
Maintain higher quality standards
Increase production capacity
Earn sustainable income
BEYOND HOME-BASED PRODUCTION, PARTICIPANTS HAVE ACHIEVED:
Started their own boutiques
Launched small fashion businesses
Offer tailoring services
Won government procurement & tender opportunities
Empowering participants to build sustainable livelihoods, achieve financial independence and create a brighter future.



NEW FINANCE FRAMEWORK






TERIMA KASIH
UNIVERSITI
TEKNOLOGI
MARA

BUSINESS ETHICS IN THE AGE OF ESG: TURNING 'GOOD INTENTIONS' INTO CREDIBLE REPORTING

Senior Lecturer Dr. Nur Aima Binti Shafie
Universiti Teknologi MARA, Malaysia



What this briefing covers.

I	**The Hook** Why ESG ethics matter now	Slides 1–4
II	**The Landscape** What ESG, ESG reporting, and the frameworks are	Slides 5–9
III	**The Credibility Gap** Greenwashing, with four global cases	Slides 10–16
IV	**The Malaysia Scenario** NSRF, Bursa Malaysia, and forced-labour WROs	Slides 17–23
V	**From Intention to Credibility** What credible reporting actually looks like	Slides 24–30

ESG, defined plainly.

E

Environmental

Climate, emissions, water, biodiversity, pollution, waste, resource use. The company's footprint on the planet.

S

Social

Labour rights, worker safety, supply-chain human rights, community impact, diversity, customer welfare.

G

Governance

Board composition, executive pay, ethics, bribery and corruption controls, transparency, shareholder rights.

The distinction that decides everything: performance vs. reporting.

ESG PERFORMANCE	ESG REPORTING
What you actually do.	*What you disclose.*
Operating decisions, capital allocation, supplier choices, hiring practices, board oversight, real-world outcomes.	The standardised, comparable, often audited account of that performance — metrics, targets, methodology, governance over the data itself.
Lives in: operations, procurement, HR, plant floor.	**Lives in: annual report, sustainability statement, regulator filings.**

Greenwashing happens when reporting outruns performance.

The reporting alphabet — simplified.

GRI	***Global Reporting Initiative*** Broad sustainability impacts; widely used since 1997. Stakeholder-focused.
SASB	***Sustainability Accounting Standards Board*** Industry-specific financially material metrics. Now consolidated under the ISSB.
TCFD	***Task Force on Climate-related Financial Disclosures*** Climate risk and opportunity disclosure structure. Recommendations absorbed into IFRS S2.
ISSB / IFRS S1 & S2	***International Sustainability Standards Board*** The new global baseline. Issued June 2023. Adopted, aligned, or in active adoption by 30+ jurisdictions, including Malaysia.

IFRS S1 & S2 — the new global baseline.

In June 2023 the International Sustainability Standards Board (ISSB) issued IFRS S1 and IFRS S2 — the first global baseline standards for sustainability and climate disclosure.

They sit alongside IFRS Accounting Standards and apply the same logic: investor-focused, comparable, decision-useful.

Malaysia adopted both through the National Sustainability Reporting Framework on 24 September 2024.

IFRS S1

General Requirements for Disclosure of Sustainability-related Financial Information

Covers governance, strategy, risk management, and metrics across all sustainability topics material to enterprise value.

IFRS S2

Climate-related Disclosures

Scope 1, 2 and 3 GHG emissions, climate-related risks, transition plans, scenario analysis, industry-specific metrics.

From ethics to enforceability.

Sustainability claims now live inside three bodies of binding law.

01

Securities & Listing Law

Misstated ESG figures in annual reports can be treated like misstated financials — triggering regulator action, restatements, and shareholder litigation.

02

Consumer Protection Law

Misleading environmental marketing claims ("green", "carbon-neutral", "sustainable") without evidence can be fined by competition and consumer authorities.

03

Trade & Supply-Chain Law

Forced-labour, deforestation and human-rights linked goods can be blocked at borders — e.g., U.S. Withhold Release Orders, EU CSDDD, EU Deforestation Regulation.

ESG is now an audit category, not a brand campaign.


Greenwashing, defined.
Greenwashing is the practice of making an environmental or sustainability claim that is unsubstantiated, exaggerated, or omits material negative information — creating an impression of responsibility that the underlying performance does not justify.
Why the term matters more in 2026
Mandatory disclosure means greenwashing now produces a paper trail.
Regulators in the EU, UK, US, Australia and Italy have all issued fines or actions since 2022.
Investor lawsuits over misleading ESG fund labels are rising.
Consumer authorities increasingly treat vague green claims as deceptive marketing.


Five common patterns of greenwashing.
1
Greencrowding
Hiding behind group initiatives or alliances to avoid individual accountability.
2
Greenlighting
Spotlighting a small green feature to distract from broader unsustainable practices.
3
Greenshifting
Blaming consumers for environmental impact rather than addressing corporate responsibility.
4
Greenlabelling
Using eco-friendly language or imagery without substantiation or evidence.
5
Greenrinsing
Repeatedly changing or weakening ESG targets so they appear consistently 'on track'.


Volkswagen — "Dieselgate" (2015).
WHAT HAPPENED
Volkswagen installed defeat-device software in roughly 11 million diesel vehicles worldwide.
The software detected emissions tests and switched on full pollution controls; on the road, NOx output reached up to 40× the legal U.S. limit.
The cars were sold under VW's "Clean Diesel" campaign — a marketing position built on the very performance that was being faked.
OUTCOME
~$33B
estimated total settlements, fines and remediation costs.
Criminal pleas in the U.S. and Germany; executives sentenced.
Class-action settlements with consumers.
Brand value collapse; multi-year share-price drag.

DWS / Deutsche Bank — the ESG label on the box (2022).

WHAT HAPPENED

DWS, Deutsche Bank's asset management arm (managing roughly €900 billion in assets), was investigated over allegations that ESG factors were not actually applied to many of the funds it marketed as 'sustainable'.

German police and prosecutors raided DWS and Deutsche Bank offices in Frankfurt in May 2022.

Separately, the U.S. SEC reached a $19 million settlement with DWS in September 2023 over misstatements regarding its ESG investment process.

OUTCOME

$19M

SEC settlement with DWS (Sept 2023) over ESG misstatements.

- CEO of DWS resigned shortly after the 2022 raid.
- Triggered a wider regulatory crackdown on ESG fund labelling across the EU and US.
- Helped drive the SEC's 2023 Names Rule update for fund marketing.

Shein — fashion claims meet a regulator (2025).

WHAT HAPPENED

In August 2025, Italy's competition authority (AGCM) fined Infinite Styles Services — the operator of Shein's European website — €1 million for misleading environmental claims.

The regulator found that marketing overstated the sustainability of certain products and used vague 'eco' language without sufficient evidence.

Part of a broader European pattern: consumer authorities are now treating unsubstantiated green claims as deceptive commercial practice.

OUTCOME

€1M

AGCM fine against Shein's European operator (Aug 2025).

- Aligns with the EU's incoming Green Claims Directive.
- Reinforces that small phrases ('sustainable', 'eco-friendly') are now treated as regulated claims.
- Reputational risk extends across all jurisdictions where the brand sells.

BP — "Beyond Petroleum" and the rebrand gap.

WHAT HAPPENED

Starting in 2000, BP launched a roughly $200 million rebranding campaign positioning itself as "Beyond Petroleum", with a green-and-yellow sunflower logo.

Subsequent analyses showed that investment in renewable energy remained a small fraction of capex — the vast majority continued to flow into oil and gas.

The 2010 Deepwater Horizon disaster released approximately 4.9 million barrels from the well (3.19 million spilled into the Gulf per the federal court finding) and exposed the gap between brand and operational reality.

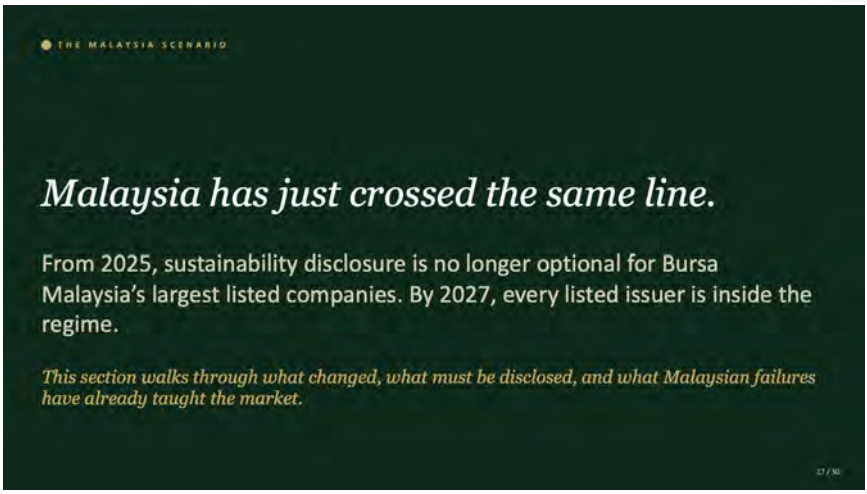
OUTCOME

>$65B

Estimated total cost to BP of Deepwater Horizon (cleanup, fines, settlements).

- Long-running case study in scholarship on greenwashing.
- Demonstrates the danger of brand outpacing capital allocation.
- BP later scaled back several climate commitments — a textbook case of greenrinsing.


What greenwashing actually costs.
Regulatory
Fines, consent orders, restated disclosures, withdrawal of product approvals or fund authorisations.
Litigation
Class actions by investors, consumer suits, derivative claims against directors and officers.
Market access
Border seizures, removal from buyer ESG-vetted supplier lists, exclusion from sustainable finance instruments.
Cost of capital
Loss of ESG fund inclusion; widening credit spreads; loss of preferential sustainability-linked loan terms.
Brand & talent
Trust erosion that takes years to rebuild; harder recruitment, particularly among younger professionals.
Operational distraction
Years of investigations, internal reviews and remediation programmes diverting management attention.


THE MALAYSIA SCENARIO
Malaysia has just crossed the same line.
From 2025, sustainability disclosure is no longer optional for Bursa Malaysia's largest listed companies. By 2027, every listed issuer is inside the regime.
This section walks through what changed, what must be disclosed, and what Malaysian failures have already taught the market.


The National Sustainability Reporting Framework (NSRF).
24 September 2024
Launched by the Securities Commission Malaysia.
The NSRF formally adopts IFRS S1 and IFRS S2 — the ISSB standards — as the applicable sustainability reporting framework for Malaysian listed companies.
This means Malaysian disclosures sit on the same global baseline used by investors in London, New York, Tokyo and Singapore.
WHO IS DRIVING THE FRAMEWORK
Securities Commission Malaysia
Owner of the NSRF; sets the overall framework and timeline.
Bursa Malaysia
Implements the disclosure rules through its Main and ACE Market Listing Requirements.
Ministry of International Trade & Industry (MITI)
Runs i-ESGStart, an ESG guide for manufacturing entities.
Bank Negara Malaysia
Aligns financial-sector climate disclosure with the NSRF (banks, insurers, takaful).

Bursa Malaysia's phased rollout: 2025 → 2027.

Three waves of mandatory IFRS S1 / S2 disclosure, sequenced by company size and market.

	WHO MUST REPORT	WHAT CHANGES
2025	Main Market issuers with market capitalisation of RM2 billion or more.	First mandatory annual sustainability statement aligned to IFRS S1 & S2.
2026	All other Main Market issuers.	Same baseline standards apply; reporting obligations broaden across the Main Market.
2027	ACE Market issuers (smaller and growth-stage listed companies).	Full population of Bursa Malaysia listed companies now inside the IFRS S1 / S2 regime.

What every reporting issuer must now disclose.

1 Governance

Board oversight of sustainability and climate; management roles; how ESG sits in strategy and risk.

2 Strategy

Material sustainability and climate risks and opportunities, and their effect on the business model.

3 Risk management

How sustainability risks are identified, assessed, prioritised and monitored alongside other enterprise risks.

4 Metrics & targets

Quantitative performance indicators — with at least three years of comparative data — and the targets that go with them.

5 GHG emissions

Scope 1, 2 and (with phase-in) Scope 3 emissions, calculated to recognised methodology and disclosed in absolute terms.

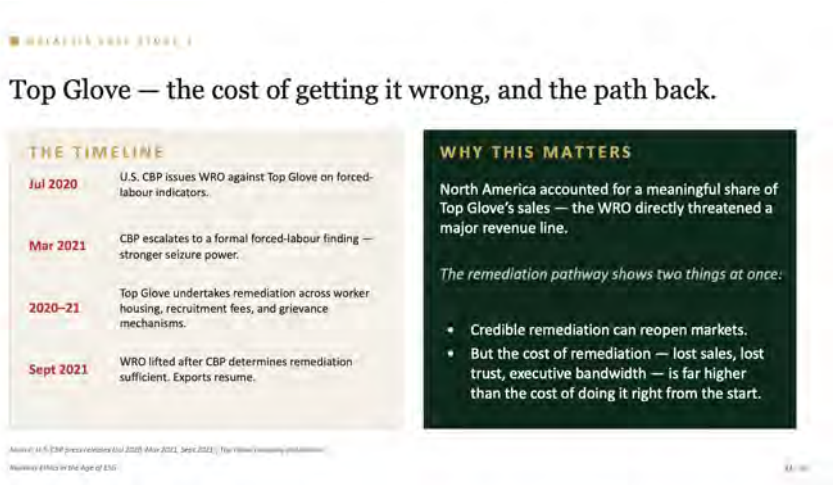
6 Assurance

An assurance statement on the sustainability report, submitted via the Bursa LINK ESG Reporting Platform.

The 'S' in ESG can shut down export markets.

Between 2020 and 2021, U.S. Customs and Border Protection (CBP) issued Withhold Release Orders (WROs) against multiple major Malaysian exporters on grounds of forced labour.

Top Glove Corporation	Jul 2020 → Sept 2021	*Disposable gloves*	WRO lifted in Sept 2021 after working/living conditions improved.
FGV Holdings	Sept 2020 (WRO)	*Palm oil*	CBP cited indicators including deception, intimidation, retention of identity documents.
Sime Darby Plantation	Dec 2020	*Palm oil*	WRO issued on palm oil and palm-oil products from Sime Darby Plantation.
Supermax / Smart Glove / Brightway	Oct – Dec 2021	*Disposable gloves*	Further WROs against Malaysian glove makers on forced-labour grounds.


Top Glove — the cost of getting it wrong, and the path back.
THE TIMELINE
Jul 2020
U.S. CBP issues WRO against Top Glove on forced-labour indicators.
Mar 2021
CBP escalates to a formal forced-labour finding — stronger seizure power.
2020–21
Top Glove undertakes remediation across worker housing, recruitment fees, and grievance mechanisms.
Sept 2021
WRO lifted after CBP determines remediation sufficient. Exports resume.
WHY THIS MATTERS
North America accounted for a meaningful share of Top Glove's sales — the WRO directly threatened a major revenue line.
The remediation pathway shows two things at once:
Credible remediation can reopen markets.
But the cost of remediation — lost sales, lost trust, executive bandwidth — is far higher than the cost of doing it right from the start.


Two gaps to close — and one cascade nobody can avoid.
THE GAPS
1. Comparability
Companies can still use different standards (GRI, SASB, TCFD) under Bursa's framework, making cross-company comparison hard. IFRS S1/S2 adoption is intended to close this.
2. Accountability for false claims
Malaysia does not yet have a dedicated anti-greenwashing enforcement regime comparable to the EU's Green Claims Directive. Penalties for misleading sustainability statements remain limited.
THE CASCADE
Listed companies are pulling their SME suppliers in.
Bursa's framework requires listed companies to report value-chain (Scope 3) emissions — which forces them to collect environmental and labour data from suppliers.
ESG questionnaires in tender documents have shifted from optional (2023) to mandatory (2024–25).
SMEs without basic ESG data are being excluded from large-company supplier lists.


Five tests for credible ESG reporting.
01
Material
Discloses topics genuinely relevant to enterprise value and to stakeholders — not a selection of flattering ones.
02
Measurable
Uses quantitative metrics with stated methodology, units, and boundaries (entity, geography, time period).
03
Comparable
Provides at least three years of consistent data so trends and trajectories can be assessed.
04
Balanced
Reports negative outcomes, missed targets and incidents — not just success stories.
05
Assured
Subject to independent third-party assurance, at a defined level (limited or reasonable).
If a claim fails any one of these, it is at best premature — at worst, actionable.

Materiality — the discipline most companies skip.

Material topics are the small set of sustainability issues that genuinely shape value, risk and stakeholder outcomes for this specific business. They are identified, not chosen for flattery.

DONE WELL	DONE BADLY
• Structured stakeholder engagement (investors, employees, regulators, community). • Risk and opportunity mapping against business model. • Threshold for materiality is disclosed. • Reviewed annually; methodology explained.	• Materiality list selected by communications team to fit the brand narrative. • No documented stakeholder engagement. • Same topics every year regardless of how the business changes. • Negative-but-relevant topics quietly omitted.

Materiality is the place where ethics enters the report — long before the metrics do.

Why third-party assurance is the credibility anchor.

Without independent assurance, an ESG report is a self-portrait. With it, it becomes evidence.

LIMITED ASSURANCE	REASONABLE ASSURANCE
"Nothing has come to our attention..."	*"In our opinion... in all material respects."*
Negative-form opinion. Lower level of testing. Most common starting point for ESG reports globally and in Malaysia.	Positive opinion. Same standard as a financial audit. Higher cost, much higher credibility. The direction of travel for major regulated markets.

The G underneath the E and the S.

Most ESG failures are governance failures first — environmental and social damage is what makes them visible.

G – 1	G – 2	G – 3
Board ownership	**Internal controls**	**Speak-up culture**
Sustainability and climate sit on a named board committee, with documented agendas and minutes. Not delegated to communications.	ESG data goes through the same control environment as financial data: defined owners, reconciliations, version history.	Functioning whistleblower channels, non-retaliation policy, and visible follow-through. Many ESG scandals were reported internally long before they were reported externally.

Strong G makes reliable E and S possible. Weak G makes reliable E and S impossible — no matter how big the marketing budget.

A pocket checklist for any ESG claim.

Before you publish — or believe — a sustainability claim, ask these seven questions.

1	Is the claim specific?	*Concrete activity, scope and timeframe — not a slogan.*
2	Is it quantified?	*Numbers with units, methodology, and a base year.*
3	Has performance been verified?	*Independent assurance, audit trail, or recognised certification.*
4	Is it comparable across time?	*Multiple years of data on the same basis.*
5	Is it material?	*Relevant to enterprise value and to stakeholder interests.*
6	Are negative outcomes disclosed too?	*Misses, incidents, and downside metrics, not just successes.*
7	Would you stand by it under cross-examination?	*Same standard as a financial statement — because legally, it now is.*

THE CORE MESSAGE

Intentions are cheap.
Credibility compounds.

Reporting is the proof, not the promise.

FOR THE MALAYSIAN MARKET

By 2027, every Bursa-listed company will be inside the IFRS S1 / S2 regime. The only open question is whether your numbers — and the systems behind them — will survive assurance.

THE ROLE OF COGNITIVE FILTERING IN AI-BASED EDUCATIONAL ACTIVITIES

Assoc. Prof. Dr. Istvan Zsigmond
Sapientia University, Romania

Abstract: *The advent of digital technology has brought about major changes in the field of education. These changes primarily concern the availability of information—and, within that, educational content—from a variety of sources. Although slowly, educational practice is adapting to the opportunities this presents. Educational practices such as blended learning, the flipped classroom, and computer-supported cooperative learning are coming to the forefront. With the availability of educational materials, the role of the educator is also changing. Instead of the traditional, primarily information-transfer-focused lecture-style methods, the educator is increasingly becoming a mentor, an agent who facilitates the learning process. Within this process, an increasingly important role is given to developing students' skills that will help them become more effective in their independent, lifelong learning process. Such skills include metacognitive thinking (particularly goal-setting and monitoring), self-regulated learning, and critical thinking. These are particularly important skills in a society where an ever-increasing abundance of information can lead to both information overload and—if appropriate self-regulated and critical skills are developed—increased productivity and greater self-fulfillment. The aim of this paper is to demonstrate how the digital environment can foster self-regulated learning and to explore the pedagogical implications of this.*

Keywords: *Self-regulated learning, Digital learning environment, Lifelong learning*

1. The Architecture of Self-Regulated Learning

Self-regulated learning is defined as an active, constructive process whereby learners set goals for their learning and attempt to monitor, regulate, and control their cognition, motivation, and behavior, guided and constrained by their goals and the contextual features in the environment. This goal-directed process relies on the complex interplay of cognition, affect, and metacognition to navigate the demands of academic tasks effectively (Lämsä et al., 2026). Specifically, this process enables individuals to strategically manage their academic pursuits through

systematic planning, monitoring, and adaptation of their cognitive and motivational states across various learning contexts (Sung et al., 2024).

This framework typically comprises three iterative phases—forethought, performance, and self-reflection—which allow students to evaluate their effectiveness and adjust their efforts toward desired outcomes (Fan et al., 2024; Lee et al., 2024). By engaging in these cyclical processes, learners essentially function as active agents who consciously adapt their strategies to bridge the gap between their current performance and their established learning objectives (Brod et al., 2023).

Beyond immediate academic performance, this mastery fosters the development of adaptive competencies that facilitate the transfer of metacognitive skills to novel, ill-structured problems outside of formal digital educational settings (Schuster et al., 2020; Taranto & Buchanan, 2020), thereby equipping learners with the resilient, lifelong learning capabilities required in rapidly evolving professional and personal landscapes (Mejeh et al., 2024; Osman et al., 2026). Empirical evidence underscores that learners who effectively navigate these phases—integrating motivational variables with metacognitive control—demonstrate superior academic persistence and achievement (Chiu, 2024).

2. Digital Tools Enhancing Self-Regulated Learning

Research on specific digital tools and strategies for self-regulated learning (SRL), such as learning management systems (LMS), mobile applications, and online forums, has emerged as a critical area of inquiry due to their growing role in enhancing learner autonomy and academic success in diverse educational contexts (Herniawati et al., 2025; Petrovic & Jaksic, 2026). Since the 1980s, SRL has been recognized as essential for academic achievement, with recent advances emphasizing digital environments that support SRL processes (Khiat & Vogel, 2022; Palalas & Wark, 2020). The integration of AI and adaptive technologies into LMS platforms has further transformed digital pedagogy by enabling personalized, interactive, and adaptive learning experiences (Afolabi et al., 2025; Padhy et al., 2025). The social and motivational dimensions of SRL are increasingly addressed through collaborative tools and real-time feedback mechanisms, highlighting the practical significance of these technologies in fostering engagement and equitable learning outcomes (Fleur et al., 2023; Suardi, 2025).

Despite the recognized importance of digital tools in supporting SRL, challenges remain in effectively aligning these technologies with learners' regulatory processes (Alvarez et al., 2022; Urbina et al., 2021). Existing research reveals a knowledge gap concerning the specific effectiveness of various digital tools—such as LMS discussion forums, mobile apps, and

AI-driven chatbots—in facilitating distinct SRL phases and strategies (Du et al., 2025; Oliha et al., 2024; Sadigzade, 2025). Moreover, controversies persist regarding the extent to which AI should supplement or replace human guidance, with some studies emphasizing the complementary role of AI and others cautioning against over-reliance (Arifin et al., 2025; Ng et al., 2024). The consequences of this gap include suboptimal learner engagement, uneven adoption of SRL strategies, and limited scalability of personalized support in large-scale or under-resourced settings (Alkhasawnh & M Alqahtani, 2019; Rizki et al., 2022). Addressing these issues is vital for advancing digital education and promoting lifelong learning competencies.

The conceptual framework underpinning this review defines self-regulated learning as a cyclical process involving forethought, performance, and reflection phases, supported by digital tools that scaffold cognitive, metacognitive, and motivational strategies (Cha & Park, 2019; Khiat & Vogel, 2022). Learning management systems, mobile applications, and online forums serve as platforms that enable goal setting, monitoring, feedback, and peer interaction, thereby fostering SRL behaviors (Liu, 2013; Rabu, 2024). The integration of AI and learning analytics further enhances this framework by providing adaptive feedback and personalized learning pathways (Afzaal et al., 2021; Ouyang, 2025). This framework guides the systematic examination of how specific digital tools and strategies facilitate SRL processes and outcomes.

The purpose of this systematic review is to synthesize current empirical evidence on the effectiveness of specific digital tools and strategies—particularly LMS, mobile apps, and online forums—in facilitating self-regulated learning. By addressing the identified knowledge gaps, this review aims to inform educators, instructional designers, and policymakers about best practices and emerging opportunities for technology-enhanced SRL support. The value of this work lies in consolidating diverse findings to guide the development of more responsive, equitable, and effective digital learning environments.

3. Methodology of literature selection

Research papers were selected by performing and online research using the query "Specific digital tools and strategies for self-regulated learning, such as learning management systems, mobile apps, and online forums, and their effectiveness in facilitating self-regulated learning.", then expanding it into multiple, more specific search statements.

A pool of 707 candidate papers was selected and impose. We found 706 papers that were relevant to the research query. A relevance ranking was imposed so that the most pertinent studies to be included in the review. Out of 706 papers, 127 were highly relevant.

Papers were included if they addressed one or more of these questions:

- Specific digital tools and strategies for self-regulated learning, such as learning management systems, mobile apps, and online forums, and their effectiveness in facilitating self-regulated learning.
- Effectiveness of learning management systems, mobile apps, forums, and adaptive feedback tools in promoting self-regulated learning: design principles, scaffolding, and outcome measures across online and blended higher education environments
- Effectiveness of integrated self-regulated learning supports across LMS dashboards, mobile micro-tools, AI-driven adaptive feedback, and peer-assisted scaffolds in online and blended higher education: a synthesis of design principles, implementation features, and learning outcomes
- What are the design principles, implementation features, and evaluation metrics that make LMS dashboards, mobile SRL apps, AI-driven feedback systems, and online forums effective at fostering self-regulated learning across online, blended, and MOOCs, and how do they compare in outcome measures (engagement, autonomy, achievement)?
- AI-enabled self-regulated learning supports in digital learning environments: real-time dashboards, adaptive feedback, and chatbots across LMS, MOOCs, and blended courses with impacts on engagement, autonomy, and achievement

4. Results

The reviewed literature presents a comprehensive examination of digital tools and strategies supporting self-regulated learning (SRL), highlighting significant advancements in adaptive technologies, learning management systems (LMS), and AI-driven feedback mechanisms. Strengths include the integration of theoretical SRL models with practical digital implementations, demonstrating positive impacts on learner motivation, metacognitive skills, and academic outcomes.

Regarding the efficiency of the digital tools, over 60 studies demonstrated that LMS platforms commonly include features such as feedback mechanisms, progress tracking, discussion forums, and adaptive content delivery that support various SRL processes (Padhy et al., 2025; Petrovic & Jaksic, 2026; Sari et al., 2024). Mobile applications and AI-driven tools provide personalized recommendations, automated feedback, and self-monitoring capabilities, enhancing learner autonomy and engagement (Arifin et al., 2025; Li et al., 2026; Oliha et al., 2024). Learning analytics dashboards and intelligent tutoring systems offer real-

time data visualization and actionable feedback, facilitating metacognitive regulation and motivation (Azevedo et al., 2022; Lee & Kim, 2024; Van Rijn et al., 2024). Some studies noted limitations in tool functionalities, such as underutilization of virtual resources or lack of comprehensive SRL process support (Alvarez et al., 2022; Valenzuela-Zambrano & Pérez-Villalobos, 2013).

As about the pedagogical integration, some of the studies aligned digital tools with established SRL theoretical models, particularly Zimmerman's cyclical model, ensuring instructional design supports planning, monitoring, and reflection phases (Arifin et al., 2025; Michael et al., 2025; Seidel et al., 2021). Integration of pedagogical frameworks with technology was evident in adaptive learning systems, blended learning designs, and MOOC interventions (Du et al., 2025; Pérez-Sanagustín et al., 2022; Yang & Yahaya, 2025). Some reviews highlighted gaps where tools lacked explicit theoretical grounding or failed to describe the relationship between functionalities and SRL processes (Alvarez et al., 2022).

Regarding learning engagement, enhanced learner motivation, participation frequency, and sustained use were reported in studies employing interactive LMS features, gamified apps, and AI chatbots (Baars et al., 2022; Petrovic & Jaksic, 2026; Sadigzade, 2025). Engagement varied by learner characteristics such as gender, academic achievement, and SRL competence, with some tools compensating for lower-achieving students (Kim et al., 2025; Uzun et al., 2025). Dashboards and feedback systems increased reflection and strategic planning but sometimes showed mixed effects on overall engagement (Borrella & Ponce-Cueto, 2025; Kia et al., 2020).

Studies reported positive impacts on academic performance, course completion rates, and knowledge retention were documented across diverse digital tools and strategies (Alkhasawnh & M Alqahtani, 2019; Du et al., 2025; Padhy et al., 2025). Some studies reported inconclusive or mixed results regarding direct academic gains despite improvements in SRL behaviors and motivation (Hsu & Tutwiler, 2022; Khiat & Vogel, 2022; Sayidiman et al., 2024). Meta-analyses and systematic reviews confirmed moderate effects of regulated learning scaffolding on academic outcomes (Shao et al., 2023).

Adaptivity and personalization is efficient with AI-driven adaptive feedback, personalized learning paths, and generative AI chatbots were effective in tailoring support to individual learner needs, promoting autonomy and sustained engagement (Li et al., 2026; Ng et al., 2024; Suazo-Galdamés & Chaple-Gil, 2025). Personalized dashboards and learning analytics facilitated targeted interventions and enhanced motivation through actionable insights (Afzaal et al., 2021; Lee & Kim, 2024). Some studies emphasized the importance of balancing AI support

with human guidance to preserve learner agency (Arifin et al., 2025; Englmeier, 2025).

5.Critical analysis and limitations

Limitations of the reviewed literature persist in methodological rigor, generalizability across diverse learner populations, and the nuanced understanding of long-term effects. Additionally, challenges remain in balancing learner autonomy with adaptive scaffolding and addressing contextual factors such as technological access and individual learner differences. The synthesis underscores the need for more robust, longitudinal, and context-sensitive research to optimize digital SRL supports.

Regarding theoretical integration and design principles, many studies effectively ground digital tools in established SRL frameworks, such as Zimmerman's cyclical model, ensuring that LMS and AI features align with cognitive, metacognitive, and motivational processes of SRL. This theoretical anchoring enhances the pedagogical relevance of tools like adaptive dashboards and personalized feedback systems, fostering learner autonomy and engagement (Alvarez et al., 2022; Khiat & Vogel, 2022; Yoon et al., 2021). Despite theoretical grounding, several tools lack explicit articulation of the SRL models guiding their design, leading to unclear connections between functionalities and SRL processes. This gap limits the ability to systematically evaluate which features most effectively support specific SRL phases (Alvarez et al., 2022).

As about methodological approaches and data quality, the literature includes diverse methodologies, from quasiexperimental designs to mixed-methods and large-scale randomized controlled trials, providing a multifaceted understanding of digital SRL interventions. Use of learning analytics and clickstream data offers objective, fine-grained insights into learner behaviors beyond self-reports (Bellhäuser et al., 2023; Kia et al., 2020; Li et al., 2020). On the other hand, many studies suffer from small sample sizes, lack of active control groups, and short-term assessments, which constrain the robustness and generalizability of findings. The predominance of self-reported measures raises concerns about the validity of SRL assessments, and few studies examine long-term effects or dose-response relationships (Eggers et al., 2021; Khiat & Vogel, 2022; Wong et al., 2019).

An important aspect of the studies as analyzing the effectiveness of AI-driven and adaptive feedback. AI-enhanced LMS and chatbots provide personalized, timely, and adaptive scaffolding that improves motivation, metacognitive reflection, and academic performance. Studies demonstrate that AI features such as predictive analytics, natural language interfaces,

and generative AI chatbots can foster sustained engagement and self-regulation (Arifin et al., 2025; Mejeh et al., 2024; Ng et al., 2024; Padhy et al., 2025). The complexity of AI integration introduces challenges including ethical concerns, data privacy, and potential over-reliance on automated feedback. Additionally, the balance between AI support and learner autonomy is delicate; some learners may underutilize or misinterpret AI scaffolds, and the effectiveness varies across learner profiles (Arifin et al., 2025; Englmeier, 2025; Mejeh et al., 2024).

What is the impact of helping SRL in digital environments on academic outcomes and motivation? Empirical evidence shows that digital SRL supports generally enhance learner motivation, engagement, and in some cases, academic achievement. Structured SRL interventions embedded in LMS and mobile apps have led to improved self-regulatory behaviors and course completion rates (Du et al., 2025; Khiat & Vogel, 2022; Sari et al., 2024). However, the impact on academic performance is often inconclusive or modest, with some studies reporting no significant differences in grades despite improvements in SRL behaviors. Variability in outcomes may be influenced by contextual factors, learner characteristics, and the quality of implementation (Hsu & Tutwiler, 2022; Khiat & Vogel, 2022; Uzun et al., 2025).

Finally, qualitative insights regarding user experience and engagement with digital tools reveal that learners appreciate ease of use, timely feedback, and interactive features in LMS, mobile apps, and dashboards, which facilitate motivation and self-monitoring. User-centered design and iterative validation enhance tool acceptance and effectiveness (Baars et al., 2022; Rabu, 2024; Rohloff et al., 2019). On the other hand, despite positive perceptions, actual usage patterns often show limited or declining engagement over time. Cognitive load, lack of training, and insufficient scaffolding can impede effective use of SRL tools. Moreover, some tools impose high inference costs or social comparison pressures that may discourage learners (Baars et al., 2022; Borrella & Ponce-Cueto, 2025; Uzun et al., 2025).

6. Theoretical and Practical Implications

Theoretical Implications

The synthesis of findings reinforces the centrality of self-regulated learning (SRL) theories, particularly Zimmerman's cyclical model, in understanding how digital tools like LMS, mobile apps, and online forums scaffold learner autonomy, motivation, and metacognition. The integration of AI-driven adaptive feedback and personalized scaffolding aligns with theoretical models emphasizing dynamic, iterative regulation of learning processes (Li et al., 2026; Michael et al., 2025; Petrovic & Jaksic, 2026).

Evidence suggests that AI-enhanced LMS platforms extend traditional SRL frameworks by incorporating real-time analytics, predictive modeling, and affective support, thus broadening the conceptualization of SRL to include hybrid human-AI interactions and emotional regulation components (Afzaal et al., 2021; Li et al., 2026; Mejeh et al., 2024).

The role of motivational and metacognitive strategies is consistently highlighted, supporting theories that posit these as critical components of effective SRL. However, some studies indicate variability in the impact of digital tools on academic performance, suggesting that SRL theories must account for contextual and individual differences in technology use and engagement (Khiat & Vogel, 2022; Sari et al., 2024; Wong et al., 2019)

The findings challenge simplistic assumptions that technology alone enhances SRL, emphasizing the need for theoretical models to integrate human factors such as learner characteristics, prior knowledge, and socio-cultural context to explain differential outcomes (Kim et al., 2025; Rizki et al., 2022; Wong et al., 2019).

The emerging evidence on the use of learning analytics dashboards and personalized feedback tools supports theoretical propositions that actionable, timely feedback is essential for fostering SRL, yet also points to the complexity of designing interventions that balance cognitive load and learner autonomy (Borrella & Ponce-Cueto, 2025; Lee & Kim, 2024; Uzun et al., 2025).

The literature underscores the importance of multi-modal data and longitudinal approaches to capture the dynamic nature of SRL in digital environments, suggesting theoretical frameworks should incorporate temporal and behavioral dimensions alongside self-report measures (Azevedo et al., 2022; Li et al., 2020; Salehian Kia et al., 2021).

Practical Implications

For educators and instructional designers, the findings advocate for the deliberate integration of AI-driven adaptive features and personalized scaffolding within LMS and mobile platforms to enhance learner engagement, motivation, and metacognitive regulation, thereby supporting more effective SRL practices (Arifin et al., 2025; Du et al., 2025; Li et al., 2026).

Institutions should prioritize professional development and training for faculty to effectively implement and leverage digital tools that support SRL, including the design of interactive content, timely feedback mechanisms, and structured SRL interventions within blended and online learning contexts (Michael et al., 2025; Molins & García, 2023; Sari et al., 2024).

Policymakers and educational technology developers are encouraged to focus on creating inclusive, equitable digital learning environments that address infrastructural disparities and provide adaptive support tailored to diverse learner needs, especially in underdeveloped or marginalized regions (Herniawati et al., 2025; Rizki et al., 2022; Suazo-Galdamés & Chaple-Gil, 2025).

The deployment of learning analytics dashboards and feedback systems should be guided by evidence-based design principles that emphasize usability, interpretability, and motivational support to maximize their impact on student self-regulation and academic persistence (Borrella & Ponce-Cueto, 2025; Uzun et al., 2025; Van Rijn et al., 2024).

Mobile learning applications and chatbots, particularly those leveraging generative AI, offer promising avenues for just-in-time support and sustained learner motivation, but require careful pedagogical integration to avoid over-reliance and ensure alignment with SRL strategies (Ng et al., 2024; Sadigzade, 2025; Wu et al., 2023).

Continuous evaluation and refinement of digital SRL tools are necessary to balance scaffold intensity and learner autonomy, ensuring that support is neither overwhelming nor insufficient, and that it adapts to evolving learner behaviors and preferences (Lim et al., 2023; Radović et al., 2024; Shao et al., 2023).

References:

1. Afolabi, I. Y., Ugah, J. O., Igwe, J. S., & Nwali, M. E. (2025). DEVELOPMENT OF AN AI-DRIVEN ADAPTIVE LEARNING MANAGEMENT SYSTEM USING DATA ANALYTICS. International Journal of Scientific Research in Modern Science and Technology, 4(7), 52-63. https://doi.org/10.59828/ijsrmst.v4i7.349
2. Afzaal, M., Nouri, J., Zia, A., Papapetrou, P., Fors, U., Wu, Y., Li, X., & Weegar, R. (2021). Explainable AI for Data-Driven Feedback and Intelligent Action Recommendations to Support Students Self-Regulation. Frontiers in Artificial Intelligence, 4. https://doi.org/10.3389/frai.2021.723447
3. Alkhasawnh, S., & M Alqahtani, M. A. (2019). Fostering Students' Self-Regulated Learning Through using a Learning Management System to Enhance Academic Outcomes at the University of Bisha. TEM Journal, 662-669. https://doi.org/10.18421/tem82-47
4. Alvarez, R. P., Jivet, I., Perez-Sanagustin, M., Scheffel, M., & Verbert, K. (2022). Tools Designed to Support Self-Regulated Learning in Online Learning Environments: A Systematic Review. IEEE Transactions on Learning Technologies, 15(4), 508-522. https://doi.org/10.1109/tlt.2022.3193271

5. Arifin, A., Pujiastuti, H., Nindiasari, H., & Ediwarman, E. (2025). Developing an AI-Based LMS to Support Self-Regulated Learning in Secondary Mathematics Education. AL-ISHLAH: Jurnal Pendidikan, 17(4). https://doi.org/10.35445/alishlah.v17i4.7686
6. Azevedo, R., Bouchet, F., Duffy, M., Harley, J., Taub, M., Trevors, G., Cloude, E., Dever, D., Wiedbusch, M., Wortha, F., & Cerezo, R. (2022). Lessons Learned and Future Directions of MetaTutor: Leveraging Multichannel Data to Scaffold Self-Regulated Learning With an Intelligent Tutoring System. Frontiers in Psychology, 13. https://doi.org/10.3389/fpsyg.2022.813632
7. Baars, M., Khare, S., & Ridderstap, L. (2022). Exploring Students' Use of a Mobile Application to Support Their Self-Regulated Learning Processes. Frontiers in Psychology, 13. https://doi.org/10.3389/fpsyg.2022.793002
8. Bellhäuser, H., Dignath, C., & Theobald, M. (2023). Daily automated feedback enhances self-regulated learning: a longitudinal randomized field experiment. Frontiers in Psychology, 14. https://doi.org/10.3389/fpsyg.2023.1125873
9. Borrella, I., & Ponce-Cueto, E. (2025). Design Principles and Impact of a Learning Analytics Dashboard: Evidence from a Randomized MOOC Experiment. Applied Sciences, 15(21), 11493. https://doi.org/10.3390/app152111493
10. Brod, G., Kucirkova, N., Shepherd, J., Jolles, D., & Molenaar, I. (2023). Agency in Educational Technology: Interdisciplinary Perspectives and Implications for Learning Design. Educational Psychology Review, 35(1). https://doi.org/10.1007/s10648-023-09749-x
11. Cha, H., & Park, T. (2019). Applying and Evaluating Visualization Design Guidelines for a MOOC Dashboard to Facilitate Self-Regulated Learning Based on Learning Analytics. KSII Transactions on Internet and Information Systems, 13(6). https://doi.org/10.3837/tiis.2019.06.002
12. Chiu, T. K. F. (2024). A classification tool to foster self-regulated learning with generative artificial intelligence by applying self-determination theory: a case of ChatGPT. Educational Technology Research and Development. https://doi.org/10.1007/s11423-024-10366-w
13. Du, J., Liu, L., & Zhao, S. (2025). Empowering Students in Online Learning Environments Through a Self-Regulated Learning–Enhanced Learning Management System. Behavioral Sciences, 15(8), 1041. https://doi.org/10.3390/bs15081041
14. Eggers, J. H., Oostdam, R., & Voogt, J. (2021). Self-regulation strategies in blended learning environments in higher education: A systematic review. Australasian Journal of Educational Technology, 175-192. https://doi.org/10.14742/ajet.6453
15. Englmeier, K. (2025). Scaffolding Autonomy: AI-Augmented Self-Paced Learning Environments for Sustainable Learning Outcomes AHFE International, http://dx.doi.org/10.54941/ahfe1006774

16. Fan, Y., Tang, L., Le, H., Shen, K., Tan, S., Zhao, T., Shen, Y., Li, X., & Gašević, D. (2024). Beware of metacognitive laziness: Effects of generative artificial intelligence on learning motivation, processes, and performance. British Journal of Educational Technology, 56(2), 489-530. https://doi.org/10.1111/bjet.13544
17. Fleur, D. S., Marshall, M., Pieters, M., Brouwer, N., Oomens, G., Konstantinidis, A., Winnips, K., Moes, S., Van den Bos, W., Bredeweg, B., & Van Vliet, E. A. (2023). IguideME. Journal of Learning Analytics, 10(2), 100-114. https://doi.org/10.18608/jla.2023.7853
18. Herniawati, A., Holifah, L., & Syakur, A. (2025). Effectiveness of Learning Management System (LMS) Use in Higher Education. International Journal Corner of Educational Research, 4(1), 20-29. https://doi.org/10.54012/ijcer.v4i1.625
19. Hsu, S.-Y., & Tutwiler, M. S. (2022, 2022/06). How Much and for Whom? Proceedings of the Ninth ACM Conference on Learning @ Scale, http://dx.doi.org/10.1145/3491140.3528312
20. Khiat, H., & Vogel, S. (2022). A self-regulated learning management system: Enhancing performance, motivation and reflection in learning. Journal of University Teaching and Learning Practice, 19(2), 43-59. https://doi.org/10.53761/1.19.2.4
21. Kia, F. S., Teasley, S. D., Hatala, M., Karabenick, S. A., & Kay, M. (2020, 2020/03/13). How patterns of students dashboard use are related to their achievement and self-regulatory engagement Proceedings of the Tenth International Conference on Learning Analytics & Knowledge, http://dx.doi.org/10.1145/3375462.3375472
22. Kim, Y., Kwak, S., & Koh, T. (2025). The Influence of Gender and Academic Achievement on University Students' Perceptions of LMS-Based Self-Regulated Learning in Korea. OBM Neurobiology, 09(04), 1-24. https://doi.org/10.21926/obm.neurobiol.2504304
23. Lämsä, J., Mooij, S. M. M. d., Baars, M., Molenaar, I., & Järvelä, S. (2026). Self-Regulated Learning, Multimodal Data, and Analysis Grid: Where Are We Now and Where Are We Going? Educational Psychology Review, 38(1). https://doi.org/10.1007/s10648-025-10113-4
24. Lee, H. Y., Chen, P.-H., Wang, W. S., Huang, Y. M., & Wu, T. T. (2024). Empowering ChatGPT with guidance mechanism in blended learning: effect of self-regulated learning, higher-order thinking skills, and knowledge construction. International Journal of Educational Technology in Higher Education, 21(1). https://doi.org/10.1186/s41239-024-00447-4
25. Lee, J., & Kim, D. (2024). From awareness to empowerment: self-determination theory-informed learning analytics dashboards to enhance student engagement in asynchronous online courses. Journal of Computing in Higher Education, 37(3), 1078-1118. https://doi.org/10.1007/s12528-024-09416-2

26. Li, Q., Baker, R., & Warschauer, M. (2020). Using clickstream data to measure, understand, and support self-regulated learning in online courses. The Internet and Higher Education, 45, 100727. https://doi.org/10.1016/j.iheduc.2020.100727
27. Li, X., Li, T., Yan, L., Li, Y., Zhao, L., Raković, M., Molenaar, I., Gašević, D., & Fan, Y. (2026). FLoRA: An advanced AI-powered engine to facilitate hybrid human-AI regulated learning. Computers & Education, 243, 105527. https://doi.org/10.1016/j.compedu.2025.105527
28. Lim, L., Bannert, M., van der Graaf, J., Fan, Y., Rakovic, M., Singh, S., Molenaar, I., & Gašević, D. (2023). How do students learn with real-time personalized scaffolds? British Journal of Educational Technology, 55(4), 1309-1327. https://doi.org/10.1111/bjet.13414
29. Liu, S. (2013). Supporting self-regulated learning with Moodle forums. 10th International Conference on Computer Supported Collaborative Learning, University of Wisconsin - Madison.
30. Mejeh, M., Sarbach, L., & Hascher, T. (2024). Effects of adaptive feedback through a digital tool – a mixed-methods study on the course of self-regulated learning. Education and Information Technologies, 29(14), 1-43. https://doi.org/10.1007/s10639-024-12510-8
31. Michael, J., B Santoso, H., Junus, K., & Sandiwarno, S. (2025). Systematic Review of Self-Regulated Learning Intervention and Measurement in Higher Education: Towards a Holistic, Integrated, and Technology-Assisted Model. Journal of Information Technology Education: Research, 24, 033. https://doi.org/10.28945/5636
32. Molins, L. L., & García, E. C. (2023). How to Embed SRL in Online Learning Settings? Design Through Learning Analytics and Personalized Learning Design in Moodle. Journal of New Approaches in Educational Research, 12(1), 120-138. https://doi.org/10.7821/naer.2023.1.1127
33. Ng, D. T. K., Tan, C. W., & Leung, J. K. L. (2024). Empowering student self-regulated learning and science education through <scp>ChatGPT</scp> : A pioneering pilot study. British Journal of Educational Technology, 55(4), 1328-1353. https://doi.org/10.1111/bjet.13454
34. Oliha, F. O., Otokiti, K. O., Idehen, D. N., Obayagbona, I. E., & Evbuomwan, I. G. (2024). Study Pal: An Automated Tool for Supporting Self-Regulated Learning Habits. Journal of Engineering Research Innovation and Scientific Development, 2(3), 1-8. https://doi.org/10.61448/jerisd23241
35. Osman, Z., Nguyen, H.-A. T., Serrano, J., Intaratat, K., & Suhandoko, A. D. J. (2026). Uncovering the Key Drivers that Strengthen Students' Academic Resilience in Open, Distance, and Digital Education Higher Institutions. International Journal of Academic Research in Accounting Finance and Management Sciences, 16(1). https://doi.org/10.6007/ijarafms/v16-i1/27421
36. Ouyang, Z. (2025). Self-regulated learning and engagement as serial mediators between AI-driven adaptive learning platform characteristics and educational

quality: a psychological mechanism analysis. Frontiers in Psychology, 16, 1646469.
37. Padhy, T. P., Malpani, D., Kumar, R., Aliwie, A. N. A., Alsailawi, H. A., & Saengkaew, W. (2025, 2025/12/12). AI-Driven Learning Management Systems: Transforming Classroom Teaching 2025 IEEE 5th International Conference on ICT in Business Industry & Government (ICTBIG), http://dx.doi.org/10.1109/ictbig68706.2025.11323565
38. Palalas, A., & Wark, N. (2020). The relationship between mobile learning and self-regulated learning: A systematic review. Australasian Journal of Educational Technology, 36(4), 151-172. https://doi.org/10.14742/ajet.5650
39. Pérez-Sanagustín, M., Pérez-Álvarez, R., Maldonado-Mahauad, J., Villalobos, E., & Sanza, C. (2022). Designing a Moodle Plugin for Promoting Learners' Self-regulated Learning in Blended Learning. In LECTURE NOTES IN COMPUTER SCIENCE (pp. 324-339): Springer International Publishing.
40. Petrovic, A., & Jaksic, D. (2026). Towards Smart and Socially Integrated Learning: A Systematic Review of LMS, Social Media and Artificial Intelligence Synergies. Electronic Journal of e-Learning, 24(1), 75-92. https://doi.org/10.34190/ejel.24.1.4417
41. Rabu, S. N. A. (2024). Students' Perceptions of Google Tools on Supporting Self-Regulated Learning in an Asynchronous Course. International Journal of Information and Education Technology, 14(6), 791-806. https://doi.org/10.18178/ijiet.2024.14.6.2104
42. Radović, S., Seidel, N., Menze, D., & Kasakowskij, R. (2024). Investigating the effects of different levels of students' regulation support on learning process and outcome: In search of the optimal level of support for self-regulated learning. Computers & Education, 215, 105041. https://doi.org/10.1016/j.compedu.2024.105041
43. Rizki, P. N. M., Handoko, I., Purnama, P., & Rustam, D. (2022). Promoting Self-Regulated Learning for Students in Underdeveloped Areas: The Case of Indonesia Nationwide Online-Learning Program. Sustainability, 14(7), 4075. https://doi.org/10.3390/su14074075
44. Rohloff, T., Sauer, D., & Meinel, C. (2019, 2019/12). Student Perception of a Learner Dashboard in MOOCs to Encourage Self-Regulated Learning 2019 IEEE International Conference on Engineering, Technology and Education (TALE), http://dx.doi.org/10.1109/tale48000.2019.9225939
45. Sadigzade, Z. (2025). Generative AI in CALL: Enhancing Self-Regulated L2 Learning Through Adaptive Chatbots. Global Spectrum of Research and Humanities, 2(6), 25-45. https://doi.org/10.69760/gsrh.0250206002
46. Salehian Kia, F., Hatala, M., Baker, R. S., & Teasley, S. D. (2021, 2021/04/12). Measuring Students' Self-Regulatory Phases in LMS with Behavior and Real-Time Self Report LAK21: 11th International Learning Analytics and Knowledge Conference, http://dx.doi.org/10.1145/3448139.3448164
47. Sari, D. F., Efendi, A., & Sumaryati, S. (2024). Empowering Higher Education Students: Enhancing Self-Regulated Learning through LMS Implementation.

Proceeding of the International Conference on Multidisciplinary Research for Sustainable Innovation, 1, 507-513. https://doi.org/10.31098/icmrsi.v1i.838

48. Sayidiman, S., Ihsan, A., Hartoto, H., Syamsuddin, A., Pagarra, H., & Hermuttaqien, B. P. F. (2024). Effectiveness of Self-Regulated Learning-Based Instruction: Enhancing Student Learning Autonomy (Study on LMS Syam-Ok UNM). Publikasi Pendidikan, 14(2), 198. https://doi.org/10.26858/publikan.v14i2.63830
49. Schuster, C., Stebner, F., Leutner, D., & Wirth, J. (2020). Transfer of metacognitive skills in self-regulated learning: an experimental training study. Metacognition and Learning, 15(3), 455-477. https://doi.org/10.1007/s11409-020-09237-5
50. Seidel, N., Karolyi, H., Burchart, M., & de Witt, C. (2021). Approaching Adaptive Support for Self-regulated Learning. In Lecture Notes in Networks and Systems (pp. 409-424): Springer International Publishing.
51. Shao, J., Chen, Y., Wei, X., Li, X., & Li, Y. (2023). Effects of regulated learning scaffolding on regulation strategies and academic performance: A meta-analysis. Frontiers in Psychology, 14. https://doi.org/10.3389/fpsyg.2023.1110086
52. Suardi, S. (2025). The Role of Real-Time Learning Analytics and Pedagogical Chatbots in Improving Digital Literacy and Self-Regulated Learning among Islamic Senior High School Students. Asian Journal of Applied Education (AJAE), 4(4), 473-486. https://doi.org/10.55927/ajae.v4i4.15369
53. Suazo-Galdamés, I. C., & Chaple-Gil, A. M. (2025). AI-Powered Adaptive Learning Systems in Higher Education: A Scoping Review of Implementation and Impact on Academic Performance. Data and Metadata, 4, 981. https://doi.org/10.56294/dm2025981
54. Sung, H., Bernacki, M. L., Greene, J. A., Yu, L., & Plumley, R. D. (2024). Beyond Frequency: Using Epistemic Network Analysis and Multimodal Traces to Understand Temporal Dynamics of Self-Regulated Learning. Carolina Digital Repository (University of North Carolina at Chapel Hill). https://doi.org/10.17615/v3k9-jx93
55. Taranto, D., & Buchanan, M. T. (2020). Sustaining Lifelong Learning: A Self-Regulated Learning (SRL) Approach. Discourse and Communication for Sustainable Education, 11(1), 5-15. https://doi.org/10.2478/dcse-2020-0002
56. Urbina, S., Villatoro, S., & Salinas, J. (2021). Self-Regulated Learning and Technology-Enhanced Learning Environments in Higher Education: A Scoping Review. Sustainability, 13(13), 7281. https://doi.org/10.3390/su13137281
57. Uzun, Y., Suraworachet, W., Zhou, Q., Gauthier, A., & Cukurova, M. (2025). Engagement with analytics feedback and its relationship to self-regulated learning competence and course performance. International Journal of Educational Technology in Higher Education, 22(1). https://doi.org/10.1186/s41239-025-00515-3

58. Valenzuela-Zambrano, B. R., & Pérez-Villalobos, M. V. (2013). Self-regulated Learning Trough the Moodle Virtual Platform. Educación y Educadores, 16(1), 66-79. https://doi.org/10.5294/edu.2013.16.1.4
59. Van Rijn, L., Karolyi, H., Hanses, M., & De Witt, C. (2024). Feedback mit Learning Analytics – Interdisziplinäres Design eines Dashboards für Studierende. Zeitschrift für Hochschulentwicklung, 19(4), 77-94. https://doi.org/10.21240/zfhe/19-4/05
60. Wong, J., Baars, M., Davis, D., Van Der Zee, T., Houben, G.-J., & Paas, F. (2019). Supporting Self-Regulated Learning in Online Learning Environments and MOOCs: A Systematic Review. International Journal of Human–Computer Interaction, 35(4-5), 356-373. https://doi.org/10.1080/10447318.2018.1543084
61. Wu, T.-T., Lee, H.-Y., Li, P.-H., Huang, C.-N., & Huang, Y.-M. (2023). Promoting Self-Regulation Progress and Knowledge Construction in Blended Learning via ChatGPT-Based Learning Aid. Journal of Educational Computing Research, 61(8), 1539-1567. https://doi.org/10.1177/07356331231191125
62. Yang, J., & Yahaya, W. A. J. W. (2025). Reimagining Instructional Design for Blended Learning in Chinese Higher Education. In Advances in Computational Intelligence and Robotics (pp. 385-404): IGI Global Scientific Publishing.
63. Yoon, M., Hill, J., & Kim, D. (2021). Designing supports for promoting self-regulated learning in the flipped classroom. Journal of Computing in Higher Education, 33(2), 398-418. https://doi.org/10.1007/s12528-021-09269-z

DIGITAL CONVERGENCE OF SMEs IN THE EUROPEAN UNION: EVIDENCE FROM THE DIGITAL INTENSITY INDEX AND THE DIGITAL DECADE 2030 FRAMEWORK (2021-2025)

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Abstract: *The digital transformation of small and medium-sized enterprises (SMEs) is a key element of the European Union's development policy, particularly in the context of achieving the objectives of the Digital Decade 2030. The aim of this article is to assess the effectiveness of the EU's digital transformation policy for enterprises in the period 2021–2025 with regard to processes of convergence in digital technology adoption across the EU-27. The empirical analysis is based on Eurostat data derived from the "ICT usage in enterprises" survey, using the Digital Intensity Index version 3 (DII v.3). Descriptive statistical methods, cluster analysis and classical β- and σ-convergence measures were applied. The results indicate an increase in the average level of digital intensity among SMEs and a reduction in disparities between countries, confirming the occurrence of convergence processes.*

Keywords: *digital transformation, digital convergence, SMEs, Digital Intensity Index (DII), Digital Decade 2030*

Introduction

The use of information technology (IT) is now one of the key determinants of business competitiveness in the digital economy. In European Union countries, the growing importance of digital technologies is evident not only in the automation of operational processes and the streamlining of management, but also in the shaping of long-term business development strategies based on innovation, the internationalisation of operations and the ability to adapt quickly to changing market conditions. The issue of digital transformation in enterprises, and in the small and medium-sized enterprise sector, is widely discussed in economic literature and public policy research. Numerous studies indicate that the use of digital technologies contributes to increased productivity, improved organisational efficiency, and enhanced innovation capacity in enterprises [8][6][5]. The phenomenon of digital transformation has led to the emergence of various theoretical and managerial perspectives on

disruptive technologies, which in turn creates a need for further research into the integration of these technologies within the ecosystem-based business models of SMEs [9]. For SMEs, digital technologies play a particularly important role, enabling them to overcome economies of scale and facilitating access to international markets [7]. The importance of the digital transformation of SMEs has been clearly emphasised in EU policy documents, including the Digital Compass 2030 [3]. One of the key objectives of this strategy is to achieve a situation by 2030 in which over 90% of small and medium-sized enterprises in the European Union will use digital technologies at least at a basic level of intensity. This objective has been further detailed in Commission Implementing Regulation (EU) 2021/1190 of 15 July 2021, laying down technical specifications for data on the topic 'ICT usage and e-commerce', adopted on the basis of Regulation (EU) 2019/2152 of the European Parliament and of the Council [2]. In this context, the basic level of digital intensity of enterprises is defined as the use of at least four of the twelve selected digital technologies, including, amongst others, cloud tools, data analytics, e-commerce and cybersecurity solutions. This level serves not only as a benchmark for monitoring the progress of SMEs' digital transformation, but also as one of the key indicators of the effectiveness of the European Union's digital policy. Despite clearly defined strategic objectives and a steady increase in the level of digitalisation among businesses in the EU, existing research indicates that significant disparities persist between Member States regarding the use of digital technologies by SMEs. Brodny and Tutak [1], in assessing the EU-27 countries in terms of the digital maturity of SMEs, demonstrated significant disparities between individual EU-27 countries and between the old and new EU member states regarding the digitalisation of SMEs. This variation raises questions about the effectiveness of the digital transformation policy being implemented in the context of convergence processes and the pace of achieving the target of 90% of enterprises having at least a basic level of digital intensity.

The aim of this study is to assess the effectiveness of digital transformation policies for businesses in the European Union in the context of the convergence of digital technology adoption levels across the EU-27, as well as to analyse progress towards the Digital Decade target, which aims for over 90% of EU SMEs to achieve a basic level of digital intensity. The analysis was carried out using the Digital Intensity Index (DII_BL v.3) for the years 2021–2025. The study was based on the preliminary assumption that convergence processes are taking place within the European Union regarding the use of digital technologies by small and

medium-sized enterprises, characterised by faster growth in digitalisation levels in countries with lower initial levels, leading to a gradual reduction in disparities between EU-27 countries.

Research material and methodology

The analysis was conducted using a convergence approach, commonly employed in research on the convergence of socio-economic development levels. The study took into account both β-type convergence, referring to the process of catching up by countries with a lower initial level of digitalisation of small and medium-sized enterprises (SMEs), and σ-type convergence, understood as the reduction in the international variation of the analysed indicator over time. This approach allows for a simultaneous assessment of the dynamics of change and the spatial variation in digital transformation processes across European Union countries. Due to the cross-sectional nature of the data and the limited number of observations, the analysis focuses on absolute β-convergence. The inclusion of additional control variables was beyond the scope of this study and is suggested as a direction for further research. This approach allows for a clear assessment of absolute convergence patterns, which are particularly relevant in the context of EU-wide digital policy evaluation.

To assess differences in the level of digitalisation within the SME sector, the Digital Intensity Index (DII) was employed. The analysis focuses on the share of enterprises that have achieved at least a basic level (BL) of digital intensity, hereafter denoted as DII_BL. This indicator captures the percentage of SMEs using a minimum threshold of digital technologies and constitutes one of the key measures for monitoring progress towards the objectives of the Digital Decade 2030, particularly in the area of enterprise digital transformation. The study uses Digital Intensity Index version 3 (DII v.3), first introduced in 2015. According to Eurostat's methodological guidelines, the composition of DII v.3 in the 2025 survey was subject to a minor modification compared to 2023, resulting from changes to question A6 concerning social media use [4]. Consequently, the component "enterprises using at least two social media platforms" was replaced by "enterprises with a website", ensuring the continued comparability of the index over the analysed period. In this study, the basic level of digital intensity is defined as an enterprise's use of at least four out of twelve selected digital technologies. In line with the objectives set out in Commission Implementing Regulation (EU) 2021/1190 and subsequent implementing acts, the Digital Decade target

stipulates that by 2030 more than 90% of SMEs in the European Union should achieve at least a basic level of digital intensity.

The study employed descriptive statistical methods and classical σ- and β-type convergence measures, enabling an assessment of changes in the level and variation of digital technology adoption by SMEs in the EU-27. σ-type convergence was assessed on the basis of changes in the population variance of the DII_BL v.3 index between the base year (2021) and the final year (2025). A decrease in the variance over time is interpreted as empirical confirmation of σ-type convergence. The hypothesis regarding β-type convergence was tested using a regression model describing the relative dynamics of the DII_BL index:

$$\ln\left(\frac{y_{i,t_0+T}}{y_{i,t_0}}\right) = a + b\ln(y_{i,t_0}) + \varepsilon_i \qquad (1),$$

where $y_{i,t}$ denotes the value of the DII_BL v.3 index in country i in period t, whilst ε_i is a random component specific to country i. A negative and statistically significant value of the parameter b confirms the occurrence of β-type convergence, indicating a faster pace of SME digitalisation in countries with a lower initial level of the DII_BL index. The β-type convergence model was estimated using the ordinary least squares (OLS) method on cross-sectional data for the EU-27 countries. Cluster analysis was performed using Ward's hierarchical method and the Euclidean distance measure.

Research results

The empirical analysis began with an assessment of the spatial variation in the rate of digital technology adoption among SMEs, as measured by the Digital Intensity Index (DII_BL v.3), across the EU-27 countries between 2021 and 2025. In 2021, DII_BL v.3 values ranged from 22.2% (Romania) to 86.1% (Sweden). By 2025, this range had narrowed to between 38.3% (Bulgaria) and 94.0% (Finland). Despite an overall increase in the level of digitalisation among SMEs across the European Union, the results indicate that significant disparities between Member States persist (Fig. 1).

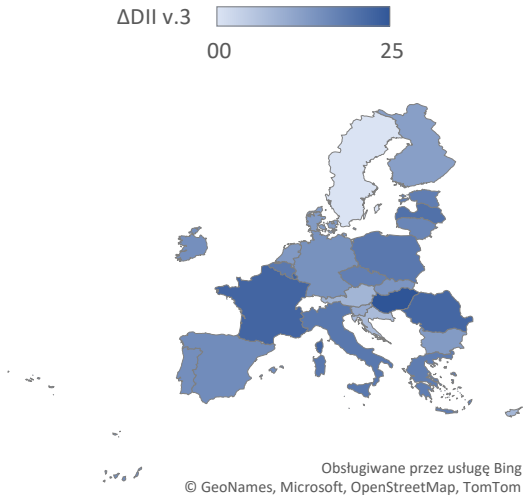


Figure 1. Spatial distribution of DII_BL v.3 in the EU-27, 2025 (% of SMEs).
Source: own elaboration based on data: [4]

The absolute increases in the DII_BL v.3 index between 2021 and 2025 ranged from 0.4 percentage points (Sweden) to 25.3 percentage points (Hungary), which in relative terms corresponded to changes ranging from 0% to 99%. Such a wide range of changes indicates that the digitalisation of SMEs proceeded in a highly varied manner across the EU-27 (Fig. 2).

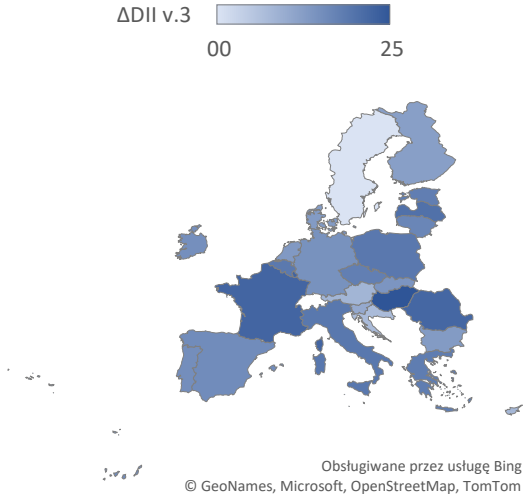


Figure 2. Spatial distribution of DII_BL v.3 changes in the EU-27, 2021–2025
Source: own elaboration based on data: [4]

Table 1 presents selected descriptive statistics for the DII_BL v.3 indicator for the EU-27 countries in 2021 and 2025. The results suggest that the EU's digital policy instruments have helped to accelerate the digitalisation of SMEs, particularly in countries with a lower baseline level. Over the period 2021–2025, the average DII_BL level rose from 55.3% to 70.6%, whilst the standard deviation fell from 16.0 to 13.6, signalling a reduction in the variation in SME digitalisation levels across EU countries.

Variable (N=27)	Mean	Median	Minimum	Maximum	Range	SD
DII_BL (2021)	55.3	55.2	22.2 (Romania)	86.1 (Sweden)	63.8	16.0
DII_BL (2025)	70.6	73.0	38.3 (Bulgaria)	94.0 (Finland)	55.7	13.6
ΔDII_BL (2021-2025)	15.3	15.3	0.4 (Sweden)	25.3 (Hungary)	24.9	5.4
%ΔDII_BL (2021-2025)	33%	30%	0% (Sweden)	99% (Romania)	99%	21%

Table 1. DII_BL v.3 – selected descriptive statistics, EU-27
Source: own elaboration based on data: [4]

Cluster analysis was used to identify countries with similar patterns of SME digitalisation, taking into account the DII_BL v.3 index level in 2025 and the change in DII_BL v.3 between 2021 and 2025. The procedure used made it possible to identify four groups of countries, characterised by different levels and dynamics of digital technology use in the SME sector (Fig. 3).

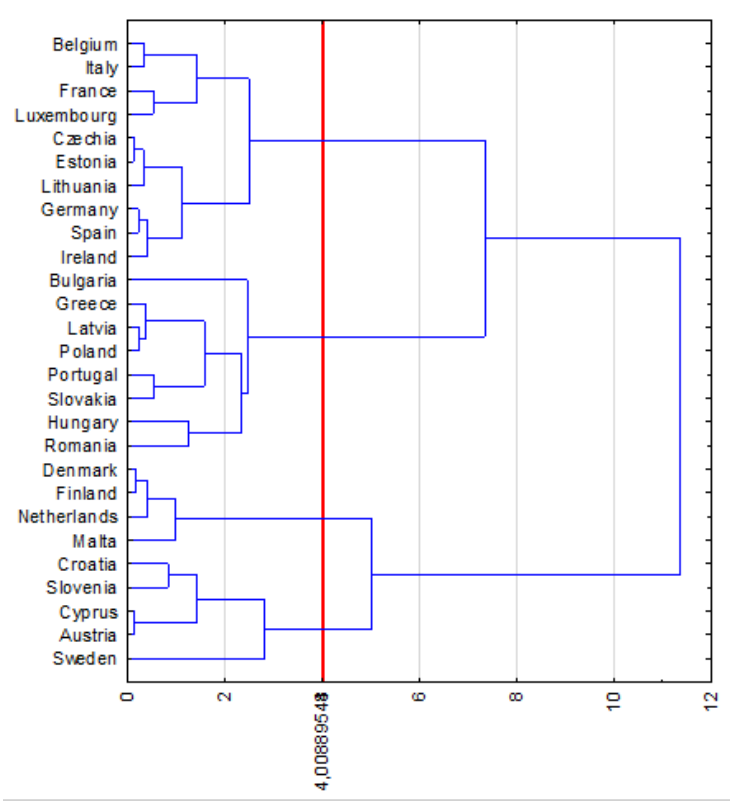


Figure 3. Cluster analysis of EU-27 countries by DII_BL v.3 level (2025) and change, 2021–2025
Source: own elaboration based on data: [4]

The results of the cluster analysis indicate clear differences among the EU-27 countries in terms of both the level and growth rate of digital technology adoption in the small and medium-sized enterprise (SME) sector, as measured by the Digital Intensity Index (DII_BL v.3). Group I comprises countries characterised by a relatively high DII_BL, accompanied by a high rate of growth in SME digital intensity between 2021 and 2025. The countries in this group can be considered leaders in digital transformation, successfully combining an advanced level of digital technology use with further progress in this area. Group IV presents a different profile, comprising countries where the level of digital technology use by SMEs is close to the EU average, but which are characterised by relatively low growth rates during the period analysed. This may indicate that a certain level of technological saturation has been reached, or that there are barriers limiting further growth in digital

intensity. Group II comprises countries with an initial DII_BL level significantly lower than the EU-27 average, which simultaneously recorded the highest growth rate in SME digital intensity between 2021 and 2025. This pattern of change confirms the presence of a catch-up effect, characteristic of convergence processes, whereby countries with a weaker starting position are closing the gap with more digitally advanced countries. The results obtained clearly confirm the heterogeneity of the EU-27 countries in terms of the level and pace of digital transformation in the SME sector. At the same time, they point to the existence of convergence processes, involving a gradual narrowing of the gaps between Member States, primarily due to the relatively faster growth in digital intensity in countries with a lower initial DII_BL score. A detailed breakdown of EU countries' membership of the identified groups is presented in Table 2.

	I (n=10)	II (n=8)	III (n=4)	IV (n=5)
Group means	DII_BL=75.4 ΔDII_BL=18.2	DII_BL=54.6 ΔDII_BL=18.5	DII_BL=89.7 ΔDII_BL=12.4	DII_BL=71.3 ΔDII_BL=7.0
Countries	Belgium, Czechia, Germany, Estonia Ireland, Spain, France, Italy, Lithuania, Luxembourg	Bulgaria, Greece, Latvia, Hungary, Poland, Portugal, Romania, Slovakia	Denmark, Malta, Netherlands, Finland	Croatia, Cyprus, Austria, Slovenia, Sweden

Table 2. EU-27 country classification by DII_BL v.3 level (2025) and change, 2021–2025
Source: own elaboration based on data: [4]

To assess the convergence of SME digitalisation levels across the EU-27 countries, a β-type convergence analysis was employed. The estimated regression coefficient took on a negative and statistically significant value of $b=-0.392$ ($p<0,001$), which confirms the occurrence of a β-type convergence process in the use of digital technologies by SMEs in the years 2021–2025. The result obtained indicates that countries with a lower initial level of the DII_BL v.3 index were characterised by a relatively faster rate of growth, suggesting a process of 'catching up' with more digitally advanced countries. The high value of the coefficient of determination ($R^2 = 0.789$) indicates a good fit between the model and the empirical data.

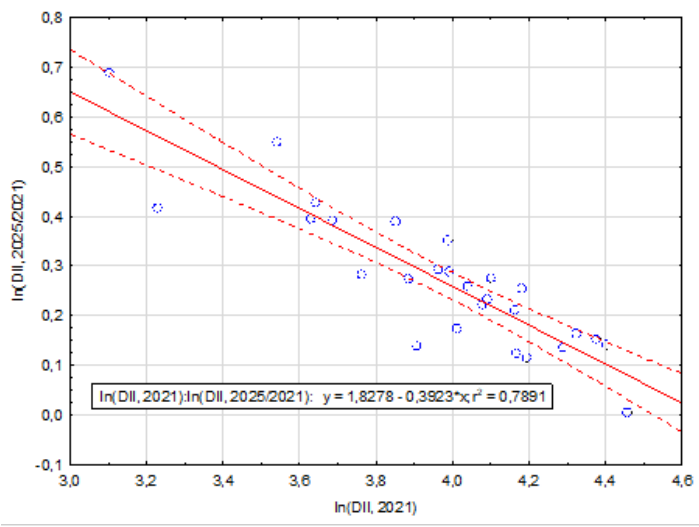


Figure 4. β-convergence estimates for SME digital technology adoption (DII_BL v.3), EU-27, 2021–2025
Source: own elaboration based on data: [4]

Table 3 presents the detailed results of the regression model estimates used to assess the occurrence of β-type convergence in the intensity of digital technology use by small and medium-sized enterprises in the EU-27 countries between 2021 and 2025, as measured by the Digital Intensity Index (DII_BL v.3).

Variable	Parameter	Estimate	Std. Error	t-statistic (df = 25)	p-value
DII_BL	a	1.828	0.161	11.332	0.000000
	b	-0.392	0.041	-9.672	0.000000

Table 3. β-convergence parameter estimates for EU-27 countries, 2021–2025
Source: own elaboration based on data: [4]

An assessment of σ-type convergence based on an analysis of changes in the variance of the DII_BL v.3 index indicates a marked reduction in the variation in the level of SME digitalisation across the EU-27 countries. The variance value fell from 257.6 in 2021 to 185.0 in 2025, which provides empirical confirmation of σ-type convergence.

Conclusions

The results of this analysis of digital technology adoption by small and medium-sized enterprises in European Union countries clearly indicate a

significant increase in the level of digital intensity among SMEs across the EU-27. The average value of the DII_BL v.3 indicator rose from 55.3% in 2021 to 70.6% in 2025, confirming the ongoing digital transformation of enterprises and the growing role of digital technologies in the functioning of the SME sector. This trend demonstrates the relatively high effectiveness of measures taken under the EU's digital policy. It should be noted, however, that despite the overall increase in the level of digitalisation, spatial analysis reveals persistent disparities between EU-27 countries. At the same time, the observed decline in the variance of the DII_BL v.3 index over the analysed period provides empirical confirmation of σ-type convergence, which implies a gradual reduction in disparities in the level of digital technology use by SMEs across Member States. The results of the β-type convergence model estimation indicate the presence of a catch-up effect, whereby countries characterised by a lower initial level of SME digital intensity achieved a relatively faster growth rate of the DII_BL v.3 index in the years 2021–2025. The negative and statistically significant value of the β parameter confirms that the digital transformation process in the EU is of a levelling nature, although its pace is not sufficient to fully eliminate differences between countries in the short term. The observed convergence processes and the increase in the DII_BL value point to a positive direction of change; however, the achievement of the Digital Decade 2030 targets, in particular the target that over 90% of EU SMEs should achieve at least a basic level of digital intensity, requires further strengthening and better targeting of support instruments, especially in countries with the lowest baseline levels and in those characterised by low digitalisation dynamics. The results obtained confirmed the convergence processes taking place in the European Union between 2021 and 2025 regarding the use of digital technologies by small and medium-sized enterprises; however, these processes were gradual and varied across different regions. This points to the need to identify both the factors determining the pace of convergence and to assess the effectiveness of specific digital policy instruments in the context of achieving the EU's long-term digital transformation goals. These findings also suggest that the EU's future digital policy should place greater emphasis on targeted support measures, tailored to the specific structural conditions of countries that are lagging behind.

References:

1. EUROPEAN COMMISSION, 2021. 2030 Digital Compass – The European way for the Digital Decade. Luxembourg: Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2759/425691
2. EUROSTAT, 2025. ICT usage in enterprises (ISOC_E) [online]. Available at: https://ec.europa.eu/eurostat [Accessed: 15 May 2026].
3. KÁDÁROVÁ, J., LACHVAJDEROVÁ, L. i SUKOPOVÁ, D., 2023. Impact of digitalization on SME performance of the EU-27: Panel data analysis. Sustainability, 15(13), art. 9973. DOI: https://doi.org/10.3390/su15139973
4. KREITERLING, C., 2023. Digital innovation and entrepreneurship: A review of challenges in competitive markets. Journal of Innovation and Entrepreneurship, 12(1), art. 49. DOI: https://doi.org/10.1186/s13731-023-00320-0
5. MASSA, S., ANNOSI, M. C., MARCHEGIANI, L. i MESSENI PETRUZZELLI, A., 2023. Digital technologies and knowledge processes: New emerging strategies in international business. A systematic literature review. Journal of Knowledge Management, 27(11), pp. 330–387. DOI: https://doi.org/10.1108/JKM-12-2022-0993
6. PICAZO RODRÍGUEZ, B., VERDÚ-JOVER, A. J., ESTRADA-CRUZ, M. i GOMEZ-GRAS, J. M., 2024. Does digital transformation increase firms' productivity perception? The role of technostress and work engagement. European Journal of Management and Business Economics, 33(2), pp. 137–156. DOI: https://doi.org/10.1108/EJMBE-06-2022-0177
7. SCUOTTO, V., CRAMMOND, R. J., MURRAY, A. i DEL GIUDICE, M., 2023. Achieving global convergence? Integrating disruptive technologies within evolving SME business models: A micro-level lens. Journal of International Management, 29(6), art. 101095. DOI: https://doi.org/10.1016/j.intman.2023.101095

ABSENTEEISM VERSUS PRESENTEEISM: A CASE STUDY OF UNISA GRADUATE SCHOOL OF BUSINESS LEADERSHIP

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Abstract: *The COVID-19 pandemic has significantly altered traditional working arrangements, prompting renewed debate regarding absenteeism and presenteeism in organisational contexts. At the University of South Africa's Graduate School of Business Leadership (UNISA GSBL), no formal policy currently governs remote working arrangements, although a council resolution encourages staff to return to on-site work. This study examines the perceived effects of absenteeism and presenteeism on employee productivity within UNISA GSBL. Using a qualitative case study approach, the study draws on sustained observational data of academic and administrative staff during two distinct periods: remote working during the COVID-19 lockdown (2020–2021), and the subsequent return to face-to-face work following the council resolution. The analysis aims to highlight the attitudes, practices and productivity of staff in both working arrangements. The results indicate that some staff has difficulty adapting to mandatory on-site work.*

They claim to be more productive when working remotely. However, as these data are confidential, due to clauses in the performance contracts, some of the data could not be independently verified. Therefore, the study is more interpretative in nature. Let us assume that perceived productivity during remote work reflects actual productivity. Then the data show that being present at work does not always lead to increased efficiency. At the same time, absentee forms of work (teleworking) do not necessarily lead to reduced productivity results. The results contradict standard statements about physical presence and productivity. They highlight the need for more systematic, empirical research on flexible working models in higher education institutions.

Keywords: *Workforce, Remote work, Absenteeism, Presence at Work, On-site Work, Organizational Productivity*

Introduction

The standard perception of work (related to physical presence in a room) has undergone a drastic transformation in the 21st century. Back in time, evidence suggests that managerial control and organizational effectiveness depended on the physical presence of employees. It can be argued that physical presence has often been associated with productivity, while absence from the physical workplace has inherently been seen as a deficit in organizational output. Contemporary factors such as technological advances and dynamic socio-economic paradigms are increasingly questioning these archaic assumptions. Thus, the spatial and temporal boundaries of work are much more flexible than previously thought.

Impact of COVID-19 on Workplace Organization

The COVID-19 pandemic has triggered an unprecedented global experiment in remote work. Many companies have changed the way they work and have been forced to transform their operations from physical offices to limit the spread of the virus (Kniffin et al., 2021). Such changes have challenged biased and outdated management rules regarding the control of employee activities and their production process. We have witnessed how many employees in the pandemic have solved complex processes, group activities or administrative duties with the same or greater efficiency from home. It has been observed that as the restrictions related to the pandemic have fallen, a deep tension has emerged between the institutional desires to return to pre-pandemic operational norms. Employees have expressed demands to maintain flexible, remote or hybrid working conditions (Wang et al., 2021).

Remote Work in Higher Education Institutions

Higher Education Institutions (HEIs) occupied a unique position during this transition. Academic work has historically possessed a degree of autonomy; however, administrative and support functions within universities have traditionally been tethered to campus offices. It is characteristic of higher education institutions that during this period they have successfully transformed research, teaching and administrative activities into online platforms (Watermeyer et al., 2021). For institutions such as the University of South Africa (UNISA), which already operates as a comprehensive Open Distance Learning (ODL) institution, there is an existing digital infrastructure. These processes have necessitated a significant change in daily activities. They appear especially for those at the UNISA Graduate School of Business Leadership (GSBL)

The Absenteeism vs. Presenteeism Debate

This operational shift has revived the academic and managerial debate around absenteeism and presenteeism. As for absenteeism, it is defined as failure to show up for scheduled work. This is largely equated with financial and operational loss to the organization (Johns, 2010). Conversely, presenteeism is the attendance at work in situations where an employee is not functioning at optimal capacity. This often occurs in

situations of job insecurity or strict attendance policies and cultural expectations (Cooper & Lu, 2016). A new situation has emerged since the pandemic, in which institutional leadership often views remote work as a form of "de facto absence" due to a lack of physical visibility.

They often exhibit a "presence" where they are physically present but are psychologically disengaged or less productive than they were remotely.

Problem Statement

At UNISA GSBL, the lack of a comprehensive, formalised policy on remote working since the pandemic has created organisational friction. A recent resolution by the University Council mandates a return to on-site work. Evidence suggests that staff is struggling to adapt to the requirement to work on-site. Many report that they have been more productive while working remotely. The underlying problem is that UNISA GSBL's drive for physical presence is rooted in traditional assumptions. For the institution, presence equals productivity. This may encourage attendance and reduce the productivity and wellbeing that staff has found during the period of remote working.

Research Objectives

The main objective of this study is to investigate the phenomena of absence and presence in the context of changing working conditions at UNISA GSBL.

Some of the objectives of this study are:

- To understand staff attitudes regarding their productivity and well-being during a mandatory period of remote work versus a mandatory period of returning to the office.
- To identify personal and organisational challenges associated with a mandatory return to on-site work.
- Critically assess whether physical presence at the UNISA GSBL campus correlates with perceived increases in employee performance.

Research Questions

To address these objectives, the study is guided by the following primary research question:

How do mandated work arrangements (remote versus on-site) influence perceived employee productivity, wellbeing, and the manifestations of absenteeism and presenteeism within UNISA GSBL?

Secondary questions include:

● What are the primary challenges experienced by academic and administrative staff upon returning to compulsory on-site work?

● How does the lack of a formalised flexible working policy impact staff morale and organisational commitment?

Significance of the study

It can be argued that this study will contribute to academic writing on the topic. The review is interesting in terms of the transition to the workplace after the pandemic, especially in higher education management. The practice provides evidence-based insights for the management of UNISA GSBL and human resource professionals. In this way, effective, contemporary, workplace policies could be developed. The study advocates for a shift to performance management based on results by examining the integration of physical presence with productivity, another ultimate goal is to improve employee well-being.

1. Literature review

1.1 Absenteeism

Absenteeism - is generally understood as the lack of physical presence at a specific workplace during scheduled working hours. Johns (2010) defines absenteeism as a complex behavior influenced by personal, social and organizational factors. It can be categorized as involuntary leave (e.g. serious illness, loss of a loved one) and voluntary leave (e.g. taking leave due to low motivation, burnout or job dissatisfaction) (Harrison & Martocchio, 1998). Some of the reasons for voluntary leave are deeply intertwined with the workplace culture. High job demands, lack of autonomy, poor support from managers and a toxic work environment are consistently associated with high levels of absenteeism (Bakker et al., 2003). On the other hand, in addition to the direct financial costs of lost hours, absenteeism disrupts work processes. It increases the burden on current employees and impairs service delivery.

Absenteeism within Higher Education Institutions In HEIs, absenteeism presents uniquely. For academic staff, whose work is inherently flexible and output-driven (e.g., publications, grant acquisitions), traditional measures of physical absenteeism are often inadequate. HEIs have historically enforced rigid attendance policies. Recent literature highlights that when universities fail to provide adequate work-life balance support, administrative absenteeism rises as a coping mechanism for stress and burnout (Smite et al., 2023). Crucially, in the contemporary era, working remotely is frequently and erroneously conflated with absenteeism by managers who rely on "management by walking around" (Bloom et al., 2015).

1.2. Presenteeism - basic definitions and concepts.

Presenteeism is a relatively new but increasingly tangible threat to organizational performance. It directly affects employee productivity. The basic definition outlines the concept as “attendance at work while sick” (Johns, 2010). Later, the concept was transformed (Cooper and Lu, 2016) and covers any situation in which an employee is physically present, but works at a suboptimal level. The reasons for this can be psychological or physical stress. It can also be due to simple “social time” without a productive outcome.

In terms of benefits, disadvantages and productivity, some scholars argue that presenteeism can serve as therapy for employees. There are situations in which if there is a mild illness, the sufferers desire social contact. In most cases, however, the majority pays more attention to its disadvantages. It is argued that presenteeism significantly limits productivity. This is because employees make more mistakes when they are physically present but disengaged. They are less creative and may exacerbate health or psychological problems (Lu et al., 2013). For example, when organizations like UNISA GSBL enforce a return to the office without considering employees' preferences for flexibility, they risk artificially inflating physical attendance rates while suppressing actual cognitive output, thereby cultivating an environment of widespread presence.

1.3. Remote Work and Productivity

The Evolution of Flexible Working Hours and the Impact of COVID-19 Remote work have been evolving since the advent of the internet. However, these models have been held back by management (Bloom et al., 2015). The COVID-19 pandemic was the catalyst that accelerated its widespread adoption. Thanks to the pandemic's constraints, remote work has gone from being a rare employee advantage to a fundamental operational necessity.

Previous studies (Bloom et al., 2015) have shown that call center employees working from home are 13% more productive. They report higher job satisfaction and lower turnover. Recent data examining the COVID-19 period replicate findings across knowledge worker sectors. Some of the benefits are increased autonomy, eliminating stress, and better work-life integration, reduced office distractions (Wang et al., 2021). However, a number of disadvantages have also been noted. They are social isolation, blurred boundaries between work and home life, and communication challenges (Oakman et al., 2020). In conclusion, it can be concluded that when implemented with adequate support, remote work maintains or improves self-reported and objective productivity.

1.4 Higher Education and Flexible Working Arrangements

Once again, universities worldwide have demonstrated remarkable flexibility during the pandemic. However, the post-pandemic period has revealed a deep divide between university administrators and staff regarding the future of work.

It is noted that a large proportion of academic staff do not approve of returning to the physical office. This is clear from more in-depth research that has already been conducted, which is more suitable for a home environment (Watermeyer et al., 2021). Administrative staff are increasingly demanding equitable flexibility, because they have proven their ability to manage university operations remotely. The main issue today is the transition from distance learning/emergency work to

sustainable, equitable hybrid policies. This would address the diverse functional needs of both academic and support staff.

1.5 Theoretical framework: The Job Demands-Resources (JD-R) model.

(JD-R) model is a basic theoretical lens (Demerouti et al., 2001; Schaufeli & Bakker, 2004). It is based on the fact that each profession has its own specific risk factors related to workplace stress. They are classified into two broad categories: job resources and job demands

- The former concern those aspects of work that are functional to achieving work goals, stimulate personal development, or reduce job demands. Examples include autonomy, flexibility, supportive leadership, and a comfortable work environment.
- The latter concern social, physical, psychological, or organizational aspects of work that require sustained effort and are associated with physiological and psychological costs. Examples include long commutes, rigid work hours, office interruptions, and inflexible administrative policies.

The conclusion is that analysis under this theory finds a relationship between productivity, well-being, absenteeism, and presenteeism. JD-R. The JD-R model explains that a prolonged imbalance—where demands are high and resources are low—leads to burnout, poor health, and ultimately absenteeism. At the same time, high job resources promote job engagement and improved productivity (Schaufeli & Taris, 2014).

This method applied at UNISA GSBL can be interpreted as follows. Remote work during the pandemic functioned as a powerful job resource (increasing autonomy and flexibility) while simultaneously reducing specific job demands (removing commuting and office politics). This explains the perceived increase in productivity. The subsequent obligation to return to the office represents the removal of a key resource (autonomy) and the reintroduction of demands (commuting, rigid schedules).

Employees who experience this resource depletion are highly susceptible to alienation and presenteeism. They appreciate the obligation to be physically present, but lack of the resources is necessary for engaged and high-quality work.

3. Research methodology

3.1 Research Design explores the various dynamics of workplace arrangements.

This study includes qualitative case study approach. It is said that qualitative research is ideally suited for examining complex social phenomena, human behaviours, and lived experiences within a specific organisational context (Yin, 2018). Such design is allowed for an in-depth, contextualised exploration of how broader trends of absenteeism and presenteeism manifest specifically within the unique environment of a South African higher education institution.

3.2 Research Setting

The research was conducted at the Graduate School of Business Leadership (GSBL) at the University of South Africa (UNISA). UNISA is Africa's largest open distance learning institution. The GSBL represents a critical node within the university, blending intensive academic research, postgraduate teaching, and complex administrative operations. The setting is highly relevant as it is currently caught between its identity as a distance-education provider and institutional mandates requiring the physical presence of its staff.

3.3 Data Collection

Data was gathered primarily through sustained participant observation. As an employee within the institution, the researcher adopted an insider-researcher perspective. This allowed clear observation of workplace dynamics and informal conversations. Observations were recorded during two distinct temporal phases:

1. The Remote Work Period (2020–2021) includes observations of virtual interactions, responsiveness, reported well-being during online meetings, and digital output metrics.

2. The Return-to-Office Period (Post-Council Resolution): Observations of staff behaviour, expressed attitudes, physical attendance patterns, and informal feedback in office corridors, staff rooms, and departmental meetings. The sample observed included a cross-section of both academic staff (professors, lecturers) and administrative/support staff (departmental administrators, HR personnel, IT support).

3.4 Data Analysis

The observational data and field notes were subjected to thematic analysis, following the guidelines set out by Braun and Clarke (2006). This involved familiarisation with the data, generating initial codes regarding staff behaviours and complaints, searching for broader themes, reviewing themes against the theoretical framework (JD-R model), and defining final thematic categories that directly address the research questions.

3.5 Ethical Considerations

Conducting insider research necessitates stringent ethical safeguards. All observations were anonymised, and no identifying characteristics of individual colleagues were recorded. A critical ethical boundary of this study is that the researcher did not have access to individual performance contracts, HR disciplinary records, or formal performance appraisal scores due to institutional confidentiality. All findings regarding "productivity" are based on perceived and self-reported productivity.

3.6 Study Limitations.

One of the main limitations is the presence of subjective factors in productivity due to the lack of access to HR performance data. Employees may have a bias towards overestimating their productivity while working from home. The study is limited to a single institution (UNISA GSBL). This fact may limit the scale of the data and conclusions and does not

provide a complete picture of different types of universities or corporate sectors. Finally, relying on observational data, although rich, does not have the statistical power of a large-scale quantitative study.

4. Findings

The data analysis revealed five distinct themes regarding the transition from remote working to mandatory on-site presence.

Theme 1: Perceived productivity during remote working here, the observations include data for the period 2020-2021.

They show a strong consensus among staff that their productivity has increased while working remotely. Academic staff often report that the isolation of the home environment facilitates "deep work"—the sustained concentration required to analyze data, write journal articles, and grade complex graduate assignments. Administrative staff also reports that the lack of occasional interruptions from "interference" has allowed them to process administrative tasks more efficiently. Although the physical campus has been "short" of staff, performance has been observed to be high. Employees have made effective use of digital tools, suggesting that the traditional definition of absence from work—equating absence from the office with a shutdown of production—has been completely redundant during this period.

Topic 2: Challenges associated with mandatory return-to-the-office policies

The board's resolution mandating a return to the physical office has been met with significant resistance and tangible friction. Observations reveal a pervasive sense of dissatisfaction. Staff highlighted the resurrection of previously eliminated job demands: gruelling commutes in Gauteng traffic, the financial costs of travel amidst rising fuel prices, and the cognitive drain of managing office politics. A recurring observational note was the phenomenon of staff commuting to the office simply to sit on Microsoft Teams or Zoom meetings with colleagues and students who were located elsewhere. This highlights a classic manifestation of presenteeism: staff complying with attendance policies for the sake of visibility, while engaging in work that could have been executed more efficiently at home.

Topic 3: Employee Autonomy and Flexibility.

This shift from remote to on-site work represents a significant loss of autonomy. In remote work, employees managed their own schedules. They worked during their most energetic hours (often early in the morning or late at night). At the same time, they were mindful of their personal responsibilities. The rigid office structure of 8:00 a.m. to 4:00 p.m. robbed them of this resource. Evidence suggests that when autonomy is taken away, intrinsic motivation decreases. Employees who had previously voluntarily worked late into the evening during the remote phase were observed to strictly adhere to the "clock-watching" behavior upon returning to the office, turning off their computers right at the end of the

official workday. Removing flexibility did not increase working hours; it simply confined them to a specific physical location.

Theme 4: Work-life balance and well-being.

In this criterion, the observational data highlights a stark contrast in employee well-being between the two periods. During the remote phase, employees reported better sleep, healthier eating habits, and stronger family connections. Returning to the office has led to observations of increased stress, fatigue, and complaints of burnout. Absenteeism, in its traditional form (taking sick leave), appears to increase after returning to the office, as staff use sick days as "mental health days" to recover from the exhaustion of the imposed routine. The organization's failure to support a transitional hybrid model negatively impacts employees' overall well-being.

Theme 5: Communication and collaboration across diverse work environments

Here we are talking about a nuanced finding about collaboration. Some employees—especially newer hires—notice that remote work hinders spontaneous collaboration and the organic transfer of institutional knowledge. Forcing everyone to return to the office at the same time, however, does not magically recreate organic collaboration. Instead, it often leads to forced, formalized meetings. Employees express a desire for purposeful presence—coming to the office specifically for collaborative workshops, team building, or strategic planning, rather than coming to the office to complete independent tasks.

5. Discussion

In conclusion, the data offer a critical intervention in the debate about absences versus presence, set in the context of a higher education institution navigating post-pandemic realities. Interpreted through the theoretical framework of Job Demands-Resources (JD-R) (Schaufeli & Bakker, 2004), the mandatory return to the office at UNISA GSBL resulted in a significant increase in work demands, while at the same time depleting key work resources (autonomy, flexibility). According to JD-R theory, this imbalance inevitably leads to burnout and alienation. Data strongly support this statement. It is said that employees reported higher stress and exhibited behaviors synonymous with presence when they are forced return. They were physically present, fulfilling the institutional requirement of "presence,". Their engagement and perceived productivity were compromised by the sudden withdrawal of their autonomy in the workplace.

The study deeply criticizes outdated management methods and defends the thesis that physical presence necessarily improves productivity. The data show that for knowledge workers—which includes both academics and senior administrative staff in a business school—the physical location of the worker is secondary to the psychological and technological

resources at their disposal. When institutional leadership views remote work solely through the lens of potential “absence,” it is applying industrial-age metrics to a digital-age workforce. The assumption that an empty office equals a lack of productivity is a fallacy, completely disproved by the resilient operations of the UNISA GSBL during a global lockdown. Conversely, the findings highlight the dangers of presence that arise from inflexible policies.

By implementing a board resolution that ignores employee preferences and the proven efficacy of remote work, the institution risks to create a culture of compliance rather than to improve engagement. Employees engaging in presenteeism—sitting at a desk to be seen by management while mentally fatigued or resentful—represent a hidden cost that is arguably more detrimental to long-term organizational goals than occasional physical absences (Cooper & Lu, 2016). Ultimately, the findings indicate that higher education workplace practices must evolve. Universities, as centres of innovation, should lead the transition toward output-driven performance metrics rather than relying on anachronistic time-and-attendance models.

6. Recommendations

Based on the findings and discussion, the following practical recommendations are proposed for UNISA GSBL, broader higher education institutions, and human resource practitioners:

1. UNISA GSBL should urgently draft and implement a formal, structured hybrid working policy. This policy should move away from binary "all-remote" or "all-onsite" models. This could allow departments to determine schedules based on operational needs. A model requiring 2-3 days on campus for collaborative work is effective. Permitting remote work for high-concentration tasks, would optimise both job resources and demands.

2. HR practitioners must separate the concepts of attendance and performance. The institution should implement output-based performance management systems. Evaluating academics and administrators on the timely, high-quality completion of deliverables, rather than the hours spent physically at a desk, will eliminate both traditional absenteeism and office presenteeism.

3. Organisational leaders should re-conceptualise the purpose of the physical campus. The office should be viewed as a destination for collaboration, ideation, and social connection. When staff are required to be on campus, it should be for activities that cannot be effectively replicated digitally, rather than for solitary administrative processing.

4. Recognising the stress associated with shifting work paradigms, UNISA GSBL should enhance wellbeing resources. Management training must be updated to equip leaders with the skills to manage distributed teams, recognise the signs of digital burnout, and manage by trust rather than by visual surveillance.

7. Conclusion

This study sought to examine the interplay between absenteeism, presenteeism, and perceived productivity at UNISA GSBL in the wake of the COVID-19 pandemic. The findings clearly demonstrate that a mandated return to the physical office, without consideration for the flexibility experienced during remote work, causes significant organisational friction.

The primary theoretical contribution of this paper is the application of the JD-R model to post-pandemic work transitions in a South African higher education context, demonstrating how the revocation of remote-work autonomy directly fuels presenteeism. The practical contribution lies in challenging institutional leadership to abandon physical presence as a proxy for performance. The study concludes that remote work should not be viewed as a form of absenteeism. On the other side, physical presence is not a guarantee of improved performance. For UNISA GSBL is important to maintain its competitiveness, to retain top talent, and foster a healthy academic community. It must embrace flexible, trust-based work arrangements that prioritise outputs and employee wellbeing over archaic notions of presenteeism.

Some of the key takeaways from this research are that distant working is not a form of absenteeism. At the same time, physical presence does not guarantee high levels of productivity. The aim of the UNISA GSBL is to foster a healthy academic community, maintain its competitive edge and support good talent.

8. Future research

Our future work builds on the new qualitative findings from this case study. Future research should consider the following directions:

- Conduct larger-scale, university-wide surveys. Use validated psychometric instruments to measure engagement, presence and perceived productivity across faculties, providing statistically aggregated data.
- To conduct comparative studies across South African universities (e.g., traditional residential universities versus comprehensive distance learning institutions). To see how institutional identity influences the success of hybrid work policies.
- To track employee well-being, retention rates, and career development over a five-year period. To assess the long-term impact of hybrid versus fully available work models.
- To find objective performance metrics: Overcome the limitations of self-reported data by partnering with HR departments (where ethically permitted) to correlate working conditions with objective performance ratings, and administrative processing times, publication outcomes

References:

1. Bakker, A. B., Demerouti, E., De Boer, E., & Schaufeli, W. B. (2003). Job demands and job resources as predictors of absence duration and frequency. Journal of Vocational Behavior, 62(2), 341-356. https://doi.org/10.1016/S0001-8791(02)00030-1
   Bakker, A. B., & Demerouti, E. (2017). Job demands-resources theory: Taking stock and looking forward. Journal of Occupational Health Psychology, 22(3), 273–285. https://doi.org/10.1037/ocp0000056
   Bloom, N. (2020). How working from home works out. Stanford Institute for Economic Policy Research (SIEPR).
2. Bloom, N., Liang, J., Roberts, J., & Ying, A. J. (2015). Does working from home work? Evidence from a Chinese experiment. The Quarterly Journal of Economics, 130(1), 165-218. https://doi.org/10.1093/qje/qju032
3. Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77-101.
4. Cooper, C., & Lu, L. (2016). Presenteeism as a global phenomenon: Unraveling the psychosocial mechanisms from the perspective of social cognitive theory. Cross Cultural & Strategic Management, 23(2), 216-231.
5. Demerouti, E., Bakker, A. B., Nachreiner, F., & Schaufeli, W. B. (2001). The job demands-resources model of burnout. Journal of Applied Psychology, 86(3), 499-512.
6. Harrison, D. A., & Martocchio, J. J. (1998). Time for absenteeism: A 20-year review of origins, offshoots, and outcomes. Journal of Management, 24(3), 305-350.
7. Johns, G. (2010). Presenteeism in the workplace: A review and research agenda. Journal of Organizational Behavior, 31(4), 519-542. https://doi.org/10.1002/job.630
8. Kniffin, K. M., Narayanan, J., Anseel, F., Antonakis, J., Ashford, S. P., Bakker, A. B., ... & Vugt, M. V. (2021). COVID-19 and the workplace: Implications, issues, and insights for future research and action. American Psychologist, 76(1), 63-77.
9. Lu, L., Lin, H. Y., & Cooper, C. L. (2013). Unhealthy and present: Motives and consequences of the act of presenteeism among Taiwanese employees. Journal of Occupational Health Psychology, 18(4), 406-416.
10. Oakman, J., Kinsman, N., Stuckey, R., Graham, M., & Weale, V. (2020). A rapid review of mental and physical health effects of working at home: how do we optimise health? BMC Public Health, 20(1), 1-13.
11. Schaufeli, W. B., & Bakker, A. B. (2004). Job demands, job resources, and their relationship with burnout and engagement: A multi-sample study. Journal of Organizational Behavior, 25(3), 293-315.
12. Schaufeli, W. B., & Taris, T. W. (2014). A critical review of the Job Demands-Resources Model: Implications for improving work and health. In G. F. Bauer

& O. Hämmig (Eds.), Bridging occupational, organizational and public health: A transdisciplinary approach (pp. 43-68). Springer Science + Business Media.
13. Smite, D., Tkalich, A., Moe, N. B., Papatheocharous, E., Poth, A., & Klotins, E. (2023). Changes in perceived productivity of software engineers during COVID-19 pandemic: The voice of evidence. Journal of Systems and Software, 197, 111550.
14. Wang, B., Liu, Y., Qian, J., & Parker, S. K. (2021). Achieving effective remote working during the COVID-19 pandemic: A work design perspective. Applied Psychology, 70(1), 16-59.
15. Watermeyer, R., Crick, T., Knight, C., & Goodall, J. (2021). COVID-19 and digital disruption in UK universities: Afflictions and affordances of emergency online migration. Higher Education, 81(3), 623-641.
16. Yin, R. K. (2018). Case study research and applications: Design and methods (6th ed.). Sage publications.

DIGITAL TRANSFORMATION AS A DRIVER OF SUSTAINABLE BLUE ECONOMY DEVELOPMENT: THE BULGARIAN CONTEXT

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Abstract: *The transition towards a sustainable blue economy has become a strategic priority for the European Union and coastal Member States, including Bulgaria. Digital transformation is increasingly recognized as a key driver of sustainability, competitiveness, and resilience across maritime sectors. This study explores the role of digital transformation as a driver of sustainable blue economy development, with a particular focus on the Bulgarian context. The research aims to assess how digital technologies contribute to sustainability and competitiveness in traditional and emerging blue economy sectors, identify the main barriers to digital transformation, and evaluate the extent to which European and national policy frameworks support this transition. The study applies a qualitative methodology combining literature review, policy analysis, desk research, and conceptual synthesis of European, national, and international strategic documents and scientific publications. The findings indicate that technologies such as artificial intelligence, the Internet of Things, digital twins, and data analytics can significantly improve operational efficiency, environmental monitoring, resource management, and maritime governance. However, the implementation of digital transformation in Bulgaria remains constrained by fragmented governance, infrastructure gaps, limited innovation capacity, skills shortages, and cybersecurity challenges. The study contributes to the literature by linking digital transformation with sustainable blue economy governance and identifying policy priorities for accelerating Bulgaria's digital and sustainable maritime transition.*

Keywords: *sustainable blue economy, digital transformation, sustainable development, governance*

The blue economy has emerged as a strategic policy priority for the European Union and its coastal Member States, reflecting the growing recognition of oceans and coastal areas as drivers of sustainable economic

development. It encompasses a wide range of traditional and emerging sectors, including fisheries, aquaculture, maritime transport, ports and logistics, coastal tourism, offshore renewable energy, marine biotechnology, and ocean observation services. At the same time, digital transformation is reshaping economic activities and governance systems worldwide. Advanced digital technologies such as artificial intelligence (AI), the Internet of Things (IoT), big data analytics, blockchain, digital twins, cloud computing, and autonomous systems are increasingly being adopted across maritime sectors. These technologies offer significant opportunities to improve operational efficiency, environmental monitoring, resource management, maritime safety, and institutional effectiveness. Recent European policy initiatives, including the Sustainable Blue Economy Strategy, the European Green Deal, and the Digital Decade Agenda, emphasize the importance of combining digital and green transitions to achieve long-term sustainability and resilience. Nevertheless, despite the growing strategic relevance of digital transformation for maritime development, substantial governance, technological, institutional, and investment challenges continue to hinder its implementation, particularly in peripheral maritime regions such as the Black Sea.

In Bulgaria, the transition towards a sustainable blue economy is further complicated by fragmented governance structures, infrastructure modernization gaps, limited innovation capacity, skills shortages, cybersecurity risks, and insufficient coordination among stakeholders. Although national strategic frameworks increasingly acknowledge the importance of digitalization and sustainability, the practical implementation of integrated digital solutions within blue economy sectors remains uneven.

Against this background, this paper examines the role of digital transformation as a strategic enabler of sustainable blue economy development, with a particular focus on Bulgaria and the Black Sea region. The study seeks to identify the opportunities created by digital technologies, assess the main barriers to implementation, and evaluate the capacity of European and national policy frameworks to support the transition towards a smart, resilient, and sustainable maritime economy.

Research Methodology

The study applies the methodological framework that combines systematic literature review, qualitative desk research, policy analysis and conceptual synthesis.

The research analyzes the official documents of international organizations and institutions (UN, OECD, EC, World Bank, etc.), national strategic documents and peer-reviewed academic publications and studies.

The analytical approach applies comparative and thematic analysis to identify strategic opportunities, implementation barriers, governance gaps, sustainability implications in the Bulgarian context.

The study analyzes the role of digital technologies and innovations for the process of transition from conventional maritime economy to sustainable blue economy, identifies the main barrires for successful implementation of digital transformation in the blue economy and the challenges in the process of transformation of the Bulgarian maritime economy into a sustainable blue economy.

Theoretical Framework: The Blue Economy Concept

The Blue Economy has emerged as a central paradigm for achieving sustainable development in coastal and marine regions. Broadly defined, it encompasses all economic activities that depend on oceans, seas, and coastal resources while ensuring their long-term environmental sustainability (Halpern et al., 2015; European Commission, 2021). Unlike traditional approaches focused primarily on the exploitation of marine resources, the Blue Economy seeks to balance economic growth, social well-being, and environmental protection through integrated and sustainable ocean governance. The concept was formally recognized during the United Nations Conference on Sustainable Development (Rio+20) in 2012. It emerged as an extension of the green economy concept, emphasizing the need to preserve the ecological integrity of marine ecosystems while unlocking the economic potential of ocean-based industries (UNEP, 2015; World Bank & UN DESA, 2017).

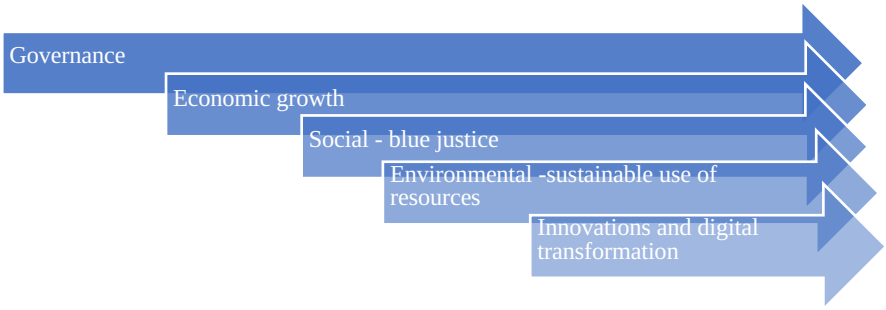


Figure 1: The five-pillars model of Sustainable Blue Economy
Source: Author's research

A growing body of literature conceptualizes the Blue Economy as a low-carbon, resource-efficient, and circular economic model. According to Giraud, Lafitte, and Fosse (2017), it promotes sustainable production and consumption patterns, creates economic value and employment opportunities, enhances social inclusion, and reduces environmental degradation. Similarly, the World Bank (2019) and WWF (2015) emphasize that the Blue Economy integrates economic development with the sustainable use of marine resources and ecosystem preservation. Although often associated with the maritime economy, the Blue Economy represents a broader and more transformative concept.

While the maritime economy traditionally focuses on economic activities conducted at sea and along coastal areas, the Blue Economy incorporates explicit sustainability objectives and adopts an integrated governance perspective that combines economic performance, environmental stewardship, and social equity (Zheng et al., 2023; Keen et al., 2018).

Recent studies increasingly identify innovation and digital transformation as critical enablers of sustainable Blue Economy development. Advanced technologies such as artificial intelligence, Internet of Things, digital twins, big data analytics, blockchain, and autonomous systems create new opportunities for improving resource efficiency, environmental monitoring, maritime safety, operational performance, and evidence-based policymaking. As argued by Bhati, Goerlandt, and Pelot (2025), technological innovation is becoming a strategic prerequisite for enhancing the sustainability, resilience, and competitiveness of both traditional and emerging blue economy sectors. This study adopts the Five-Pillar Model of Sustainable Blue Economy, which conceptualizes sustainable maritime development through five interrelated dimensions: economic growth, environmental sustainability, social inclusion and blue justice, effective governance, and innovation-driven digital transformation. Particular attention is paid to the fifth pillar, innovation and digital transformation, which is examined as a cross-cutting driver enabling the transition towards a smart, resilient, and sustainable blue economy.

Defining Digital Transformation in the Context of the Blue Economy

Within contemporary blue economy research, innovation and digital transformation are increasingly viewed not merely as supporting instruments but as strategic drivers of sustainable maritime development.

The ability of maritime sectors to achieve higher levels of productivity, environmental performance, resilience, and competitiveness increasingly depends on the adoption of advanced digital technologies and data-driven governance models. Digitalization enables more effective management of marine resources, improves operational efficiency, strengthens maritime safety and security, and supports evidence-based policymaking. Consequently, the concept of a sustainable blue economy is evolving towards the notion of a "smart blue economy", where technological innovation and sustainability objectives are mutually reinforcing. This perspective places digital transformation at the centre of contemporary debates on maritime governance and sustainable development.

Digital transformation is defined not merely as technological modernization, but as a systemic transformation process affecting governance, economic models, infrastructure systems, organizational structures, and social interactions. The European Commission's Digital Decade Strategy further conceptualizes digital transformation as a strategic enabler of sustainability transition.

According to the European Commission (EC, 2021), digital transformation represents the integration of digital technologies across society and the economy, fundamentally changing how public institutions, businesses and citizens operate, interact and create value The OECD (2022) defines digital transformation as the economic and societal effects of digitization and digitalization resulting from the combined adoption of digital technologies and data-driven innovation. From a strategic management perspective, Vial (2019), George et al. (2021) argue that digital transformation should be understood as a multidimensional organizational and governance transformation process integrating innovation ecosystems, institutional adaptation, and sustainable value creation.

Digital transformation encompasses the strategic integration of advanced technologies such as artificial intelligence, internet of things, big data analytics, cloud computing, and mobile technologies into all areas of business and business operations (Cennamo et al., 2020; Li et al., 2024). Researches, as Beulen and Bode (2021), Li et al. (2024), Agustian et al.(2023), Shostak et al. (2024) conclude that the digital transformation fundamentally alters the business models and brings radical improvement and innovation to an entity (organization, business network, industry, or society).

- The EU Blue Economy Report 2025 identifies innovations and digitalization as major drivers of economic growth,

competitiveness, and sustainability in maritime sectors. OECD (2023) stresses that digitalisation and automation can increase the efficiency of maritime economies while reducing pressure on ecosystems. Consequently, digital transformation within the blue economy represents a strategic governance paradigm combining technological innovation, sustainability objectives, maritime security, and long-term resilience.

Benefits of Digital Transformation across Blue Economy Sectors

The blue economy differs from traditional maritime economic models through its emphasis on sustainability, circularity, innovation, and ecosystem protection. Rahal (2025) argues that digital technologies support sustainable ocean governance, marine resource optimization, climate resilience, integrated environmental monitoring, and smart maritime management systems. Within this context, digital transformation has emerged as a key enabler of sustainable maritime development.

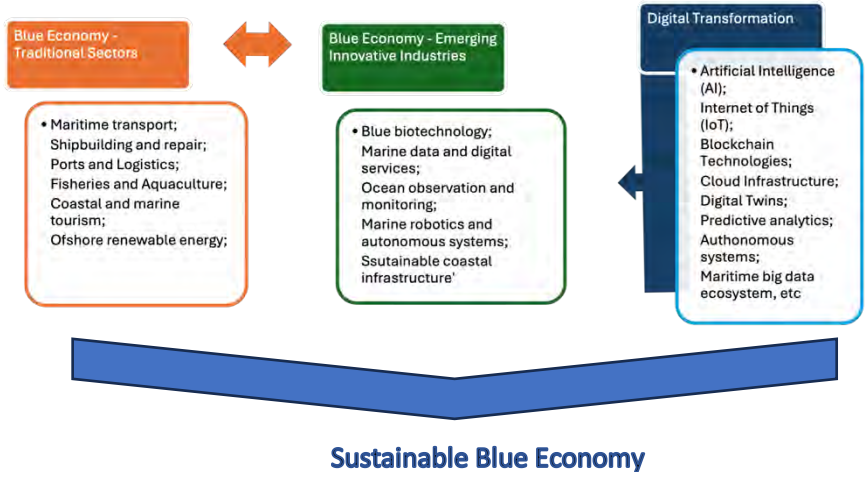


Figure 2 Digital transformation as an enaber of transition to sustainable blue economy
Source: Author's research

Digital transformation is reshaping the operational, economic, environmental, and governance dimensions of both traditional and emerging blue economy sectors (Figure 2). Existing research demonstrates that increasing environmental pressures, efficiency requirements, and competitiveness challenges are among the main drivers accelerating digital adoption across maritime industries (Wang & Su, 2021; Rahal, 2025).

The rapid expansion of the digital economy has profound implications for ocean-based industries. Maritime transport, fisheries, aquaculture, coastal tourism, shipbuilding, offshore renewable energy, and port logistics are undergoing significant transformation driven by artificial intelligence, automation, big data analytics, cloud platforms, and integrated digital systems. Evidence from scientific studies and policy reports suggests that these technologies contribute not only to operational efficiency and economic performance but also to sustainability, climate resilience, maritime safety, and resource optimization. Table 1 summarises the benefits.

Table 1. Benefits of Digital Transformation and AI Across Traditional and Emerging Blue Economy Sectors
Source: Author's research

Blue Economy Sector	Digital and AI Applications	Strategic Benefits
Maritime transport	AI route optimization, autonomous navigation, predictive maintenance	Reduced emissions, fuel efficiency, operational optimization
Ports and logistics	Smart ports, IoT, automated cargo systems, digital twins	Faster logistics, resilience, reduced congestion
Fisheries	AI-supported monitoring, satellite analytics, blockchain traceability	Sustainable resource management, reduced illegal fishing
Aquaculture	Smart sensors, AI water quality management, predictive feeding systems	Higher productivity, lower environmental impact
Coastal tourism	Smart tourism platforms, AI visitor analytics, digital destination management	Sustainable tourism management, resource optimization
Shipbuilding and repair	Digital twins, robotics, AI-supported engineering	Reduced production costs, improved safety and efficiency
Offshore renewable energy	Predictive maintenance, AI grid management, smart energy systems	Energy resilience, decarbonization, operational reliability
Blue biotechnology	Big data analytics, AI-supported marine bioresource research	Innovation capacity, sustainable bio-based products
Marine data and digital services	Cloud systems, maritime big data platforms	Data-driven governance and interoperability
Ocean observation and monitoring	Satellite systems, AI environmental analytics	Climate resilience and ecosystem protection
Marine robotics and autonomous systems	Autonomous underwater vehicles, AI-supported surveillance	Maritime security and operational efficiency
Sustainable coastal infrastructure	Smart coastal monitoring systems, digital climate risk platforms	Coastal resilience and adaptive governance

The growing importance of digital transformation is reflected in recent industry trends. According to Khaskheli, Zhao, and Lai (2025), approximately 78% of maritime companies accelerated digital transformation initiatives during the COVID-19 period, investing in technologies such as artificial intelligence, cloud computing, blockchain, and digital twins. Similarly, the global smart ports market is projected to reach USD 15.5 billion by 2032, highlighting the increasing strategic role of digital infrastructure in maritime competitiveness (Port Technology, 2023). The literature further demonstrates that digital technologies generate significant sustainability benefits across blue economy sectors. Artificial intelligence and advanced analytics improve route optimization, predictive maintenance, and fuel efficiency in maritime transport; support sustainable fisheries management through monitoring and traceability systems; enhance aquaculture productivity through smart sensing technologies; and strengthen environmental protection through real-time ecosystem monitoring. As noted by Jiang et al. (2024), digital technologies contribute to sustainable improvements in marine productivity, while Elston and Nogueira (2024) emphasize the central role of digital innovation in advancing blue economy objectives.

Digitalization also facilitates market access, reduces transaction costs, and supports evidence-based decision-making. Studies by Khaskheli (2025) indicate that digital technologies can simultaneously improve business performance and reduce environmental impacts, particularly in fisheries, coastal tourism, and marine trade. Similarly, IoT-enabled ecosystems have demonstrated significant potential for empowering coastal communities and improving the sustainability of small-scale fisheries (Anand et al., 2024).

Despite these benefits, important barriers continue to limit the adoption of digital technologies within the blue economy. Adhiatma et al. (2023) identify limited digital literacy, inadequate infrastructure, restricted access to finance, and resistance to organizational change as major constraints, particularly for micro, small, and medium-sized enterprises, which constitute a significant share of blue economy actors. These challenges highlight the importance of integrated governance frameworks, targeted investment policies, and capacity-building initiatives to ensure that the benefits of digital transformation contribute effectively to sustainable blue economy development.

Digital Transformation, Innovation and Sustainable Blue Economy Development: The Bulgarian Context

For Bulgaria, the Black Sea represents not only a valuable ecological asset but also a strategic economic and geopolitical interface. The sustainable development of the blue economy is increasingly recognized as an important opportunity for enhancing national competitiveness, supporting regional development, creating high-value employment, and preserving marine and coastal ecosystems. Bulgarian scholars have highlighted the growing importance of the blue economy as a framework for balancing economic growth with environmental sustainability and resource conservation (Baltov, 2018; Baltov, 2019; Marenova, 2018; Shivarov, 2022; Nikolova & Bartos, 2025).

Despite its favourable geographical location, rich marine resources, and access to European funding instruments, Bulgaria's blue economy remains relatively underdeveloped and fragmented compared to other European maritime economies (World Bank, 2020). The transition towards a sustainable blue economy is influenced by a complex interaction of European policy priorities, national institutional capacities, technological readiness, and regional geopolitical dynamics. Nikolova (2026). As a result, the development of a sustainable and digitally enabled blue economy has become an increasingly important strategic objective within Bulgaria's long-term development agenda.

National Policy Framework

The analysis of strategic documents shows that Bulgaria is making progress in transposing European approach combining green transition and digital transformation as interconnected strategic objectives. The strategic direction of Bulgaria's digital and innovation transition is outlined in several national policy documents.



Figure 3: Policy Framework. National Context; Source: Author's research

Several strategic documents provide the foundation for this transition. The National Development Programme Bulgaria 2030 identifies digital transformation, innovation, connectivity, and institutional modernization as essential prerequisites for sustainable growth. The Innovation Strategy for Smart Specialisation 2021–2027 promotes research and innovation ecosystems, digital entrepreneurship, technological modernization, and university–industry cooperation. Similarly, the National Recovery and Resilience Plan allocates substantial resources to digital infrastructure, cybersecurity, innovation capacity, green mobility, and public-sector modernization.

Sector-specific policies further support the transition towards a smart and sustainable maritime economy. The Programme for Transport Connectivity 2021–2027 promotes the modernization and digitalization of transport and logistics infrastructure, while the Maritime Spatial Plan of the Republic of Bulgaria establishes a framework for integrated maritime governance and sustainable marine resource management. The Integrated Transport Strategy to 2030 emphasizes smart mobility, intelligent transport systems, multimodal connectivity, and decarbonization. In parallel, the National Cybersecurity Strategy "Cyber Resilient Bulgaria 2023" addresses the growing need to protect critical infrastructure and strengthen cyber resilience across increasingly digitalized sectors.

Tourism, which remains one of the most significant components of Bulgaria's blue economy, is also undergoing digital transformation. The adoption of smart tourism solutions and digital destination management systems is increasingly recognized as a mechanism for improving resource efficiency, destination resilience, and the sustainability of coastal tourism development.

Implementation Gap and Governance Challenges

Despite the growing alignment between national and European strategic priorities, the implementation of digital transformation within Bulgaria's blue economy remains uneven. The analysis of policy documents and institutional reports reveals a persistent gap between strategic ambitions and practical implementation. Although Bulgaria has successfully transposed many European regulatory requirements, the effective implementation of policies and achievement of strategic objectives continue to face significant challenges (World Bank, 2020).

One of the most significant barriers relates to fragmented governance structures. Responsibilities for maritime governance, environmental protection, transport, innovation, cybersecurity, tourism, and coastal

development remain distributed across multiple institutions with limited coordination mechanisms. This institutional fragmentation often results in overlapping responsibilities, administrative inefficiencies, delayed implementation processes, and insufficient interoperability among governance systems. (Nikolova, 2024; Word Bank, 2020)

Structural Barriers to Digital Transformation

The analysis of data from the EU Blue Economy Observatory indicates persistent investment challenges across several blue economy sectors in Bulgaria. Trends in investment intensity and value-added generation suggest that technological modernization remains insufficient to support a comprehensive digital and green transition. Limited investment in infrastructure modernization, restricted access to advanced technologies, and inadequate innovation capacity continue to constrain sectoral competitiveness. (Nikolova, 2026)

Infrastructure deficiencies remain particularly visible in maritime transport, port operations, fisheries, and coastal logistics systems. Compared with leading European maritime hubs, the integration of smart port technologies, digital logistics platforms, and advanced automation systems remains relatively limited.

Another critical challenge concerns the low level of digital maturity across maritime sectors. According to the European Innovation Scoreboard (2024), Bulgaria remains an emerging innovator, with declining levels of business expenditure on research and development and decreasing rates of product and process innovation among SMEs. Furthermore, the country's eco-innovation performance remains significantly below the European Union average, limiting the capacity of businesses to simultaneously pursue digital and sustainability objectives.

Human capital constraints further complicate the transition process. The successful implementation of artificial intelligence, maritime digitalization, cybersecurity solutions, and smart governance systems requires highly specialized skills in data analytics, maritime informatics, digital engineering, and information security.

However, demographic decline, labour shortages, brain drain, and insufficient interdisciplinary training continue to undermine the availability of qualified professionals (4BIZ, 2023).

Environmental pressures also remain significant. Marine pollution, biodiversity loss, coastal erosion, and climate-related risks increasingly threaten the sustainability of Bulgaria’s coastal regions. While digital technologies, artificial intelligence, and big-data analytics offer substantial

opportunities for predictive environmental management and evidence-based policymaking, their practical application within environmental monitoring systems remains relatively limited.

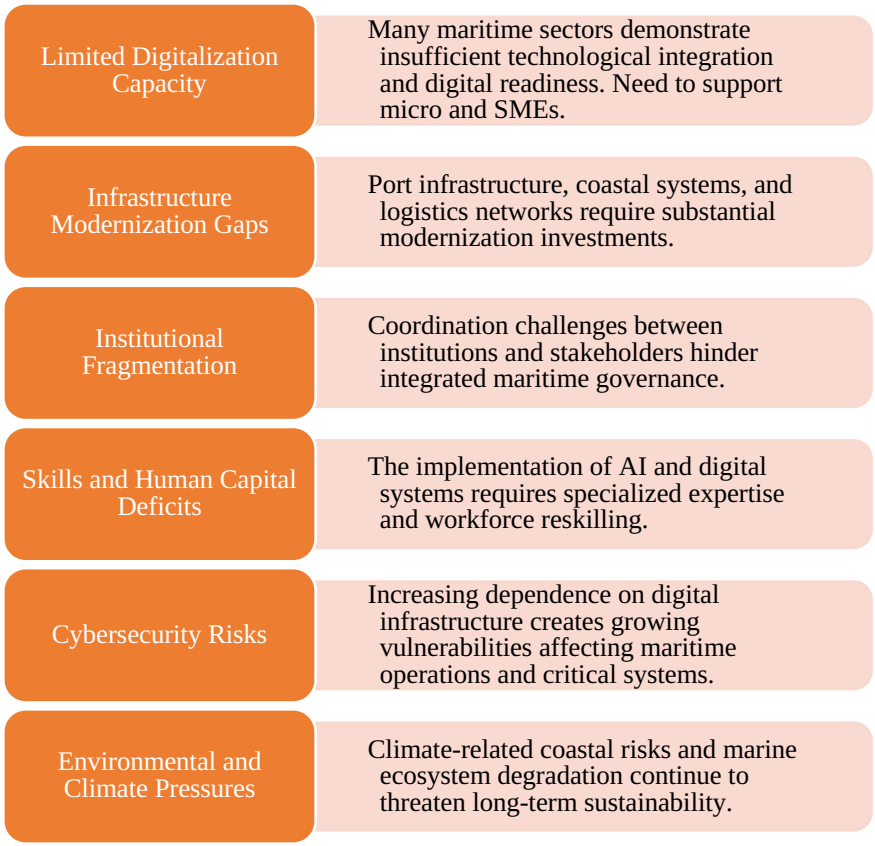


Figure 4: Structural Challenges; Source: Author's research

Security and Regional Cooperation Challenges

As maritime infrastructure becomes increasingly digitalized, cybersecurity has emerged as a critical dimension of sustainable blue economy governance. Ports, logistics systems, transport corridors, offshore energy facilities, and digital platforms are becoming progressively more exposed to cyberattacks, hybrid threats, and operational disruptions.

In addition, the geopolitical environment of the Black Sea region has elevated the importance of regional cooperation and maritime security. Limited cross-border coordination continues to affect transport connectivity, environmental protection, maritime safety, and economic

cooperation. Existing regional initiatives, including the Black Sea Synergy, the Common Maritime Agenda for the Black Sea, the Strategic Research and Innovation Agenda (SRIA), the Interreg NEXT Black Sea Basin Programme, and the Black Sea Economic Cooperation (BSEC), provide important frameworks for collaboration, yet their implementation remains uneven.

The adoption of the European Union's renewed Strategic Approach to the Black Sea in 2025 reflects the increasing recognition that sustainable blue economy development, digital transformation, regional security, and economic resilience are deeply interconnected policy priorities. For Bulgaria, successfully addressing these challenges will be essential for strengthening the competitiveness, sustainability, and resilience of its maritime economy in the coming decade. (EC, 2024; EC, 2025)

Conclusions

The transition towards a sustainable blue economy increasingly depends on the successful integration of digital transformation. For Bulgaria and the wider Black Sea region, this transition represents not only a technological challenge but also a strategic opportunity to enhance economic competitiveness, environmental sustainability, institutional resilience, and regional cooperation.

The findings indicate that Bulgaria has made significant progress in aligning its national strategic priorities with European policies promoting the twin green and digital transition. Key policy documents increasingly recognize the importance of digital infrastructure, innovation ecosystems, smart specialization, transport modernization, cybersecurity, sustainable tourism, and integrated maritime governance as essential components of sustainable development.

However, the analysis also reveals persistent implementation challenges that continue to constrain the transformation process. These include fragmented governance structures, insufficient technological integration across maritime sectors, limited innovation capacity, infrastructure modernization gaps, shortages of qualified human capital, and restricted access to investment resources. Such barriers reduce the ability of maritime stakeholders to fully exploit the benefits of digital technologies and innovation.

The study further confirms that cybersecurity and maritime security are becoming increasingly important dimensions of sustainable blue economy governance. As ports, logistics systems, transport networks, and energy infrastructure become more digitalized, their exposure to cyber threats and

hybrid risks increases, requiring stronger institutional preparedness and resilience.

Overall, the findings support the argument that digital transformation functions as a strategic enabler of sustainable blue economy development. The transition towards a smart and sustainable blue economy requires integrated governance frameworks capable of simultaneously addressing technological modernization, environmental sustainability, economic competitiveness, institutional effectiveness, cybersecurity, and regional cooperation.

For Bulgaria, the successful implementation of this transition will depend on strengthening institutional coordination, fostering innovation ecosystems, investing in digital and maritime infrastructure, developing specialized human capital, and improving cybersecurity resilience. These measures are essential for enhancing the long-term sustainability, resilience, and competitiveness of the Bulgarian maritime economy within the evolving European and Black Sea policy environment.

References:

1. Балтов, М., 2018. The Blue Economy'investments promotion, Международна научна конференция на тема „Синя икономика и синьо развитие“, БСУ
2. Балтов, М., 2019. Стратегически дневен ред за изследвания и иновации в Черно море в посока 2030г., Юбилейна международна конференция Съвременни управленски практики X, Бургаски свободен университет.
3. Димов, С.Х., 2018.Лидерство в научните изследвания, свързани с иновации в устойчивата океанска и крайбрежна икономика (Blue economy), Международна научна конференция на тема „Синя икономика и синьо развитие“, БСУ
4. Маренова, В., 2018. Устойчиво развитие на синята икономика и влиянието й върху крайбрежния туризъм (Изследване - анкетно проучване), Международна научна конференция на тема „Синя икономика и синьо развитие“, БСУ
5. Николова, А. & Харизанова-Бартос, Х., 2025. Тенденции в развитието на синята икономика на България, Международна научна конференция Съвременни управленски практики XII,Сборник доклади, БСУ
6. Шиваров, А., 2022. The Blue Economy of the Western Black Sea, Известия на Съюза на учените - Варна. Серия Икономически науки 3:44-52.

7. Adhiatma, A., Fachrunnisa, O., Nurhidayati, N., & Rahayu, T. P., 2023. Creating digital ecosystem for small and medium enterprises: The role of dynamic capability, agile leadership and change readiness. Journal of Science and Technology Policy Management, 14(5), 941–959. https://doi.org/10.1108/JSTPM-12-2020-0171
8. Agustian, K., Mubarok, E. S., Zen, A., Wiwin, W., & Malik, A. J., 2023. The impact of digital transformation on business models and competitive advantage. Technology and Society Perspectives, 1(2), 79–93. https://doi.org/10.61100/tacit.v1i2.55
9. Anand, S. et al., 2024. Internet over the ocean: A smart IoT-enabled digital ecosystem for empowering coastal fisher communities, Technol. Soc., vol. 79, 102686.
10. Beulen, E., & Bode, R., 2021. An information technology and innovation committee to guide digital transformations. Corporate Board: Role, Duties and Composition, 17(2), 38–53. https://doi.org/10.22495/cbv17i2art4
11. Bhati, M., F. Goerlandt, and R. Pelot., 2025. Digital twin development towards integration into blue economy: A bibliometric analysis, Ocean Eng., vol. 317, 119781
12. Cennamo, C., Dagnino, G. B., Di Minin, A., & Lanzolla, G., 2020. Managing digital transformation: Scope of transformation and modalities of value co-generation and delivery. California Management Review, 62(4), 5–16. https://doi.org/10.1177/0008125620942136
13. Elston, H. Pinto, and C. Nogueira., 2024. Tides of Change for a Sustainable Blue Economy: A Systematic Literature Review of Innovation in Maritime Activities," Sustain., vol. 16, pp. 1–27.
14. European Commission, 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a new approach for a sustainable blue economy in the EU. Transforming the EU's blue economy for a sustainable future. COM (2021) 240 final.
15. European Commission, 2025. The EU Blue Economy Report, Publication office of the EU, Luxemburg.
16. European Commission, 2024. European Innovation Scoreboard 2024 – Country profile Bulgaria, Brussels
17. European Commission, 2025. Joint Communication to the European Parliament and the Council, the European Union's Strategic Approach to the Black Sea. Brussels.
18. 4BIZ (Boosting the Blue Economy in the Black Sea Region by Initiating a Business Collaboration Framework in the field of Fisheries and Aquaculture, Coastal and Maritime Tourism and Maritime Transport), 2023. D 2.1 – Country reports regarding the Blue Business sectors in Romania, Bulgaria, Turkey Georgia and Ukraine, available at: https://4biz.bsun.org/

19. Giraud, J., Lafitte, A. and Fosse, J., 2017. Blue economy; economic activities and sustainable development. The blue plan. Notes 34.Valbonne, France
20. George, G., Merrill, R. K., & Schillebeeckx, S. J., 2021. Digital sustainability and entrepreneurship: How digital innovations are shaping social and environmental sustainability. Journal of Management Studies, 58(4), 999–1027. doi.org
21. Halpern, B.S. and others, 2015. Spatial and temporal changes in increasing human impacts on the world's ocean. Nature Communications 6, 7615.
22. Jiang, Y.L. Huang, Y. Liu, and S. Wang., 2024. Impact of Digital Development and Technology Innovation on the Marine Fishery Economy Quality, Fishes, vol. 9, pp. 1–20.
23. Khaskheli, M.B.; Zhao, Y.; Lai, Z., 2025. Sustainable Maritime Governance of Digital Technologies for Marine Economic Development and for Managing Challenges in Shipping Risk: Legal Policy and Marine Environmental Management. Sustainability 17, 9526. https://doi.org/10.3390/su17219526
24. Khaskheli, M. B., 2025. Sustainable maritime governance of digital technologies: Artificial intelligence and blockchain opportunities in the blue economy. Sustainability, 17(21), 9526. https://doi.org/10.3390/su17219526
25. Keen, M.R., A.M. Schwarz and L. Wini-Simeon, 2018. Towards defining the Blue Economy: Practical lessons from Pacific Ocean governance. Marine Policy 88, pp. 333-341
26. Li, Z., Gong, P., Wang, Y., & Qu, S., 2024. The impact of digital transformation on enterprise organizational structure. Highlights in Business, Economics and Management, 41, 732–740. https://doi.org/10.54097/qt9jer93
27. Nikolova, A., 2026. Challenges for sustainable blue economy development in Bulgaria. Fifth International Conference – IDARA 2025. Conference Proceedings, UNWE
28. Nikolova, A., 2024. Transition to a sustainable blue economy – from a global framework to a national context. Forth International Conference IDARA-2024. Conference Proceedings pp.301-314, UNWE.
29. OECD, 2016. The Ocean Economy in 2030. Paris: OECD
30. OECD, 2020. Strategic approaches to digital transformation: An integrated policy framework. OECD Publishing. doi.org
31. Rahal, I., 2025. The blue economy in the digital age: How information technology drives sustainable ocean development MPRA Paper No. 127349. University Library of Munich.
32. Shostak, L., Lipych, L., Fedoniuk, A., Volynets, I., Ulyanytsky, A., & Morokhova, V., 2024. Business models of enterprises in the conditions of digital transformation: Global and domestic experience. Economics, 12(2), 243–261. https://doi.org/10.2478/eoik-2024-0027
33. United Nations Environment Programme, 2015. Blue economy: Sharing success stories to inspire change. Nairobi: UNEP.

34. Vial, G., 2019. Digital transformation: A multidisciplinary reflection and research agenda. The Journal of Strategic Information Systems, 28(2), 118–144. doi.org
35. Wang, X.; Ma, C.; Yao, Z., 2024. The double-edged sword effect of digital capability on green innovation: Evidence from Chinese listed industrial firms. Econ. Anal. Policy 2024, 82, 321–339.
36. World Bank & UN DESA, 2017. The Potential of the Blue Economy: Increasing Long-term Benefits of the Sustainable Use of Marine Resources for Small Island Developing States and Coastal Least Developed Countries. World Bank, Washington DC
37. World Bank, 2019. Blue economy development framework. Washington, DC: World Bank.
38. World Bank, 2020. Bulgarian Blue Economy, Policy Note. Toward a Blue Economy development, World Bank.
39. World Wide Fund for Nature, 2015. Principles for a Sustainable Blue Economy; Available at: www.panda.org/wwf_news/?247477/Principles-for-a-Sustainable-Blue-Economy.

CULTURE AND THE CULTURE MANAGEMENT IN THE WORKPLACE

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Abstract: *Organisational culture constitutes a critical determinant of institutional cohesion, employee integration, and overall organisational performance. This study examines the nature and management of workplace culture within the context of the University of South Africa (UNISA) Graduate School of Business Leadership. It explores how cultural dynamics manifest in everyday staff interactions and how these dynamics influence the integration of new employees.*

Using an observational and interpretive research approach, the study focuses on interpersonal relations and organisational responses to cultural diversity. Particular attention is given to onboarding practices and managerial interventions in shaping cultural alignment. Drawing on theoretical perspectives from cultural studies, organisational behaviour, and social psychology, the paper situates workplace culture as both a system of shared meanings and a dynamic process subject to managerial influence.

The findings reveal the complex interplay between individual cultural orientations and institutional norms, highlighting the indispensable role of leadership in fostering cohesion and inclusivity. The study concludes that strategic cultural management is essential for enhancing organisational effectiveness and sustaining a shared value system.

Keywords: *Organisational culture, Cultural diversity, Employee integration, Leadership*

Introduction

Organisational culture remains a fundamental construct in understanding the functioning and effectiveness of modern institutions. Culture influences behavior, communication, decision-making processes, and the integration of employees into organisational life. As globalisation and workforce diversity intensify, managing cultural complexity becomes increasingly critical for organisational sustainability.

This paper investigates workplace culture within the UNISA Graduate School of Business Leadership, with a specific focus on employee interactions and integration processes. It aims to analyze how culture is constructed, maintained, and managed, and how it affects organisational cohesion.

2. Literature Review

2.1 Conceptualizing Organisational Culture

Organisational culture can be understood as a system of shared values, beliefs, and practices that shape behavior within institutions. Richerson and Boyd (2006) conceptualize culture as an evolutionary system of socially transmitted behaviors that influence group coordination and adaptation. This perspective emphasizes that culture is not static but continuously reproduced through social interaction.

Similarly, Ghauri and Buckley (2003) highlight the significance of cultural context in organisational settings, particularly in shaping communication patterns and managerial effectiveness within diverse environments.

2.2 Cultural Diversity and Social Dynamics

Cultural diversity in organizations often leads to both opportunities and challenges. Monin et al. (2013) argue that social identity and moral judgments play a significant role in how individuals evaluate others' behaviors within cultural contexts. This can result in implicit biases, which may affect workplace relationships and inclusion.

Tedeschi and Riess (1981) further assert that interpersonal influence processes are central to organisational interactions, suggesting that individuals constantly negotiate identity and power within cultural frameworks.

2.3 Motivation, Job Design, and Cultural Integration

Hackman and Oldham's (1975) Job Characteristics Model provides insight into how organisational structures influence employee motivation and integration. They propose that meaningful work, autonomy, and feedback enhance employee engagement, which is closely linked to cultural alignment.

Gardner and Martinko (1988) extend this discussion by emphasising impression management in organizations, suggesting that employees adapt behaviors to align with perceived cultural expectations. This process plays a key role in how new employees integrate into existing organisational cultures.

2.4 Cultural Evolution and Management

Houdek (2016) argues that cultural evolution within organizations is shaped by incentives, norms, and institutional frameworks. Effective culture management requires intentional strategies that align organisational goals with employee behaviour.

This aligns with Richerson and Boyd's (2006) assertion that institutional leadership plays a crucial role in reinforcing cultural norms through structured practices and policies.

3. Methodology

This study adopts a qualitative observational approach, focusing on interpersonal interactions within the workplace. Data were gathered through:

- Direct observation of staff interactions
- Informal engagement with employees
- Analysis of organisational practices related to onboarding and integration

This approach aligns with interpretive research paradigms, which emphasise understanding social phenomena within their natural context (Ghauri & Buckley, 2003).

4. Findings and Discussion

4.1 Cultural Manifestations in the Workplace

The findings indicate that workplace culture is expressed through daily interactions, communication styles, and informal norms. Employees exhibit varying cultural orientations, often shaped by personal backgrounds and professional experiences.

These variations can lead to both synergy and tension, particularly in collaborative tasks. As Monin et al. (2013) suggest, moral evaluations and social judgments influence how employees perceive one another, which can either strengthen or weaken team cohesion.

4.2 Integration of New Employees

The onboarding process plays a critical role in cultural transmission. New employees often rely on observation and social cues to understand acceptable behaviour. However, inconsistencies in cultural signalling can create ambiguity, hindering integration.

Gardner and Martinko (1988) note that individuals often engage in impression management during this phase, attempting to conform to perceived expectations. Without clear guidance, this process can lead to misalignment between personal and organisational values.

4.3 Role of Leadership in Culture Management

Leadership emerges as a central factor in shaping organisational culture. Managers influence cultural norms through:

- Communication practices
- Decision-making processes
- Reinforcement of shared values

Hackman and Oldham (1975) highlight the importance of structured roles and feedback mechanisms in fostering engagement, which supports cultural integration.

Houdek (2016) further emphasises that leadership must actively design systems that promote desirable behaviours, ensuring alignment between institutional objectives and employee actions.

4.4 Challenges in Managing Cultural Diversity

The study identifies several challenges, including:

- Implicit biases among employees

- Lack of standardized onboarding practices
- Variability in communication styles
- Resistance to cultural change

These challenges underscore the need for deliberate and inclusive cultural management strategies.

5. Conclusion

This paper highlights the complexity of organisational culture and its profound impact on employee integration and institutional cohesion. The findings demonstrate that culture is both a product of individual interactions and a construct shaped by leadership and organisational systems.

Effective culture management requires intentional strategies that promote inclusivity, clarity, and alignment with organisational goals. Leadership plays a pivotal role in fostering a cohesive environment that accommodates diversity while maintaining shared values.

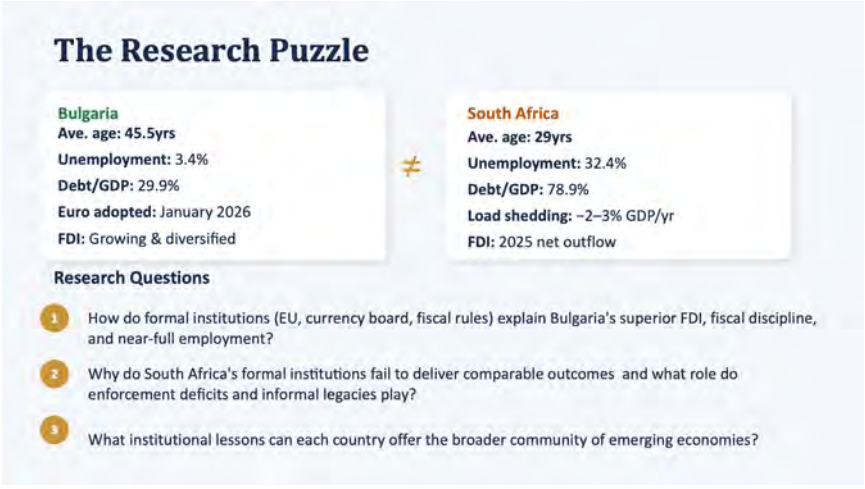
Future research should explore the impact of digital transformation on organisational culture and the role of hybrid work environments in shaping cultural dynamics.

References:

1. Gardner, W. L., & Martinko, M. J. (1988). Impression management in organizations.
2. Ghauri, P., & Buckley, P. (2003). International Business Research Methods.
3. Hackman, J. R., & Oldham, G. R. (1975). Development of the Job Characteristics Model.
4. Houdek, P. (2016). Cultural evolution and organisational behaviour.
5. Monin, B., et al. (2013). Moral judgments and social identity in organisations.
6. Richerson, P. J., & Boyd, R. (2006). Not by Genes Alone: How Culture Transformed Human Evolution.
7. Tedeschi, J. T., & Riess, M. (1981). Identities, the phenomenal self, and laboratory research.

INSTITUTIONAL ECONOMICS ANALYSIS OF GROWTH DRIVERS AND GLOBAL COMPETITIVENESS: A COMPARATIVE STUDY OF BULGARIA AND SOUTH AFRICA

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University of South Africa (UNISA)





Methodology

Comparative Institutional Analysis

1. Describe formal institutional framework
2. Assess enforcement effectiveness
3. Trace historical path of institutional change
4. Identify complementarities or inconsistencies
5. Link institutional configurations to outcomes

Data Sources

World Bank WGI (2024)
Rule of law, regulatory quality, government effectiveness, corruption control

IMF / SARB / BNB / Eurostat (2024–26)
Macroeconomic data: debt, FDI, employment

EU accession & Operation Vulindlela reports
Process tracing of reform trajectories

Bulgaria: The EU as Institutional Anchor

Acquis Communautaire

- Binding domestic law post-2007
- Solves credible commitment problem
- Infringement proceedings deter reneging
- Cooperation & Verification Mechanism (until 2023)

Currency Board → Euro

- Fixed lev:euro 1.95583 since 1997
- Outsources monetary credibility to ECB
- Eliminates FX risk for eurozone trade
- Euro adopted 1 January 2026

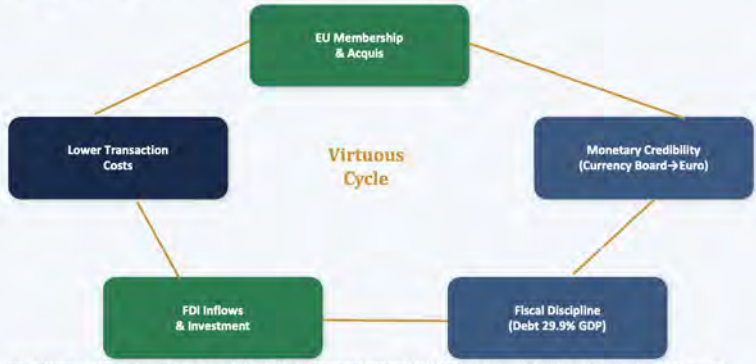
Fiscal Rules

- Organic Budget Law (EU-mandated)
- Stability & Growth Pact obligations
- Debt/GDP: 29.9% — lowest in EU
- External enforcement via EC sanctions

Labour Market Flexibility

- Fixed-term contracts, flexible hours
- Low redundancy costs vs. W. Europe
- Unemployment: 3.4% (2025)
- Wage growth: 13.4% YoY Q2 2025

Bulgaria's Virtuous Institutional Cycle



Key Evidence: €1bn Rheinmetall JV chose Bulgaria for 'institutional stability', 'EU legal framework', 'predictable tax regime'. FDI surveys (BNB, 2026) confirm institutional factors dominate location decisions — not only labour cost.

South Africa: Strong Constitution, Weak Enforcement

The Critical Gap: De Jure vs. De Facto Institutions

Institutional Domain	De Jure (Formal)	De Facto (Actual)	Gap?
Property Rights	§25 Constitution: robust protection	Policy uncertainty; land reform rhetoric	⚠ High
Contract Enforcement	Independent judiciary; Constitutional Court	WJP civil justice score: 0.52/1.0	⚠ Moderate
Corruption Control	Criminalised; Zondo Commission held	Systemic state capture legacy	⚠ High
Fiscal Rules	PFMA; Medium-term framework	Debt/GDP 78.9%; missed deficit targets	⚠ High
Infrastructure Governance	Companies Act; SOE boards	Eskom/Transnet institutional failure	⚠ Critical

WGI 2024: Rule of Law 60th percentile | Government Effectiveness 48th percentile | Corruption Control 45th percentile

South Africa's Core Institutional Failure: Infrastructure Governance

Energy (ESKOM company-Monopoly) — **–2 to –3% GDP/year**

Load shedding estimated to reduce GDP growth by 2–3 pp annually (SARB, 2025). Plant availability failure is not technical — it is institutional: misaligned incentives, political interference, no credible penalties for poor performance.

Logistics (Transnet as a major State Owned logistics company) — **Significant export revenue loss**

Port backlogs and rail network deterioration raise export transaction costs and reduce mining export volumes. SOE governance structure prioritises political objectives over commercial viability.

Institutional Economics Verdict: Elevated transaction costs — unpredictable supply, planning difficulties, backup expenses — directly reduce firm competitiveness and deter investment.

Labour & Fiscal Institutions: A Tale of Two Systems

Bulgaria

Labour Market

- Flexible fixed-term contracts
- Wage growth: 12.7% YoY
- Low redundancy costs
- Unemployment: 3.4% (2025)

Fiscal Institutions

- Signals: no expropriation risk to investors
- Organic Budget Law + SGP obligations
- Debt/GDP: 29.9% (EU's lowest tier)
- External EC sanctions for fiscal slippage

South Africa

Labour Market

- South Africa's formal labour rules are well designed
- Labour Relations Act — high dismissal costs (were designed to address historical/colonial unfair labour practices which did not protect black workers
- Sectoral bargaining raises hiring costs
- Unemployment: 32.4%; dual market
- Formal rules designed for Nordic context, applied in low-capacity environment

Fiscal Institutions

- Political override of fiscal rules via supplementary budgets
- PFMA exists but weak external enforcement
- Debt/GDP: 78.9% — rising trajectory
- SOE bailouts override deficit targets

Key insight but institutionally inconsistent applied in a weak-state-capacity environment, they raise hiring transaction costs without delivering Nordic-style security.

Comparative Institutional Matrix

Institutional Domain	Bulgaria	South Africa
Rule of Law / Contract Enforcement	Moderate — EU monitoring raises enforcement	Moderate — strong courts, weak state capacity
Property Rights Security	High — EU framework	Moderate — constitutionally strong, policy uncertainty
Corruption Control	Weak but improving under EU pressure	Weak — state capture legacy (Zondo Commission/ Madlanga Commission)
Fiscal Rules & Enforcement	High — EU Stability and Growth Pact	Moderate — rules exist, no credible external enforcer
Monetary Institution	Currency board → Euro (highly credible)	**Independent central bank (credible)**
Labour Market Flexibility	High — 3.4% unemployment	Low — 32.4% unemployment
Infrastructure Governance	Moderate — improving with EU funds	Weak — Eskom, Transnet failures
External Institutional Anchor	Strong — EU, euro	**Weak — AfCFTA (shallow integration)**
Institutional Complementarity	High — virtuous cycle	Low — inconsistent domains

Path Dependence & External Anchoring: Why History Matters for Reform

Bulgaria's Path

- **1990s** — Post-communist transition; hyperinflation crisis
- **1997** — Currency board established — removes monetary discretion
- **2007** — EU accession — acquis becomes binding domestic law
- **2023** — CVM closed; EU Rule of Law mechanism continues
- **2026** — Euro adopted — path dependence completes to full anchor

South Africa's Path

- **1994** — Democratic transition — strong 1996 Constitution
- **2000s** — Growth era; SARB independence; ANC dominant party
- **2009–18** — State capture; SOE governance collapses
- **2022** — Zondo Commission (state capture investigation); Reform momentum (Op. Vulindlela)
- **2025/26** — Madlanga Commission (On law enforcement &Political interference)
- Slow recovery; institutional inconsistency persists

Path dependence insight:

- *Bulgaria cannot simply import South Africa's resource wealth, nor can South Africa simply copy Bulgaria's EU anchor. Reform must work with, and gradually reshape, inherited institutional structures.*

Key Findings

1. **External Anchors Solve Credible Commitment Problems**

   Bulgaria's EU membership provides binding enforcement that no domestic institution can replicate. Supranational oversight lowers transaction costs across all investment domains simultaneously.

2. **Institutional Complementarity Creates Virtuous Cycles**

   Bulgaria: EU conditionality + currency board + fiscal rules = self-reinforcing competitive advantage. South Africa: strong monetary institution + weak infrastructure = inconsistency that nullifies gains.

3. **Enforcement Gap Explains South Africa's Institutional Paradox**

   Strong de jure constitution + weak de facto enforcement = elevated transaction costs despite formal rule-of-law credentials. The Zondo Commission revealed systemic enforcement failure.

4. **Transaction Costs, Not Factor Endowments, Drive Divergence**

   South Africa has more natural resources. Bulgaria has better institutions. Better institutions win. Rolling blackouts, port delays, and policy uncertainty each add measurable transaction cost premiums.


Policy Recommendations
For South Africa to escape the Low-Equilibrium Trap
Deep AfCFTA Integration
Pursue binding investment, competition & dispute resolution protocols — seek supranational enforcement as external anchor
SOE Governance Reform
Independent boards, performance-based contracts, hard budget constraints; remove political appointment from operations
Two-Tier Labour Reform
Flexible contracts for new entrants (youth, low-skilled); protect existing workers — reduce hiring transaction costs
Legislated Debt Ceiling
Automatic corrective mechanisms + independent fiscal council monitoring — create credible fiscal commitment without EU
For Bulgaria to sustaining Competitiveness
Anti-Corruption via EPPO
Fully utilise European Public Prosecutor's Office; judicial independence is the GII drag (81st)
Demographic Reform
Skilled immigration, foreign qualification recognition, childcare support to address labour force contraction
Capital Market Depth
Alternative financing beyond bank lending for innovative firms; leverage euro to deepen financial integration


Lessons for Emerging Economies
L1
External Anchors Substitute for Weak Domestic Commitment
Deep regional integration with enforceable rules can solve credible commitment problems that domestic politics cannot. AfCFTA must deepen — mere tariff reduction is insufficient.
L2
Design Institutions as Complementary Systems
Fiscal rules, monetary stability, and open markets reinforce each other. One weak domain (e.g. infrastructure) elevates transaction costs that undermine otherwise strong institutions.
L3
Informal Institutions Constrain Formal Reform
Bulgaria's communist-era clientelism and South Africa's apartheid-era inequality create informal norms that formal rules alone cannot erase. Reform must account for these.
L4
Conditionality Works When Credible, Sustained & Incentivised
EU conditionality (funds + market access + binding rules) has outperformed episodic IMF conditionality. The combination of rewards and sanctions is the key design principle.


Conclusions
Bulgaria's superior performance is attributable to a coherent set of complementary institutions anchored by EU membership.
Transaction costs:
Systematically lower in Bulgaria — euro, EU legal remedies, functioning infrastructure vs. blackouts, port delays, policy uncertainty
Credible commitment:
EU membership solves what no domestic institution can: the time-inconsistency problem of emerging-economy governance
South Africa's paradox:
Strong constitution + independent SARB + weak SOE governance = low-institutional equilibrium trap with path-dependent constraints
Reform imperative:
Institutional reform must reduce transaction costs, strengthen commitment mechanisms, and leverage regional integration as anchor
Muchara, B. · Institutional Analysis of RSA and Bulgaria · June 2026 · Thank you — Questions welcome

ERP-DRIVEN CIRCULAR MANUFACTURING: INTEGRATING PRODUCTION PLANNING, FINANCIAL ACCOUNTING, AND COST CONTROLLING

Lecturer Dr. Sînziana Rindasu
Bucharest University of Economic Studies, Romania

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ERP-driven circular manufacturing: Integrating production planning, financial accounting, and cost controlling

"Digital Twins for a Circular Future"

Lecturer Sînziana RÎNDAŞU, Ph.D
Bucharest University of Economic Studies, Faculty of Accounting and Management Information Systems
Department of Management Information Systems

ERP-driven circular manufacturing: production, accounting and controlling perspectives

- Digital transformation
- Circular economy
- ERP systems
- Digital twins
- Production planning
- Financial accounting
- Cost controlling
- Case study



What is digital transformation and why it matters?

Definition: the process of using advanced digital technologies to fundamentally change how businesses operate and deliver value to their customers.

It is more than just digitizing existing processes - it involves rethinking entire business models and creating a culture of continuous innovation and adaptation.



Digital transformation

Digital transformation in practice

How Starbucks is using data and AI to deliver joy and connection to its customers
(Forbes, 2025)

- **Personalized customer experience**
- **Mobile ordering and digital payments**
- **Data-driven decision-making**
- **AI-supported store operations**
- **Human-centered AI, not technology for its own sake**



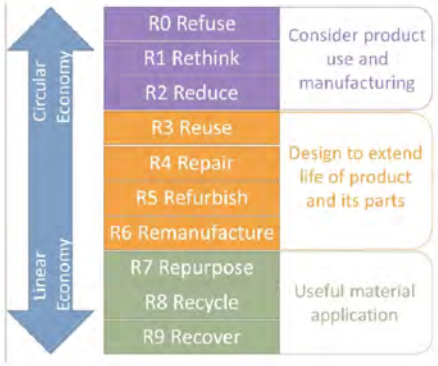
Circular economy

The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.

- **Protecting the environment** (80% of a product's environmental impact is determined during the design phase)
- **Reducing raw material dependence**
- **Creating jobs and saving consumers money**



The 9R's framwork

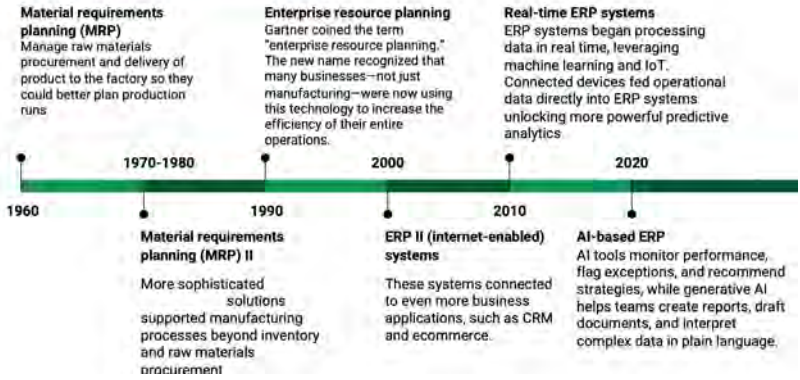


Enterprise resource planning (ERP) systems

Definition: Enterprise resource planning (ERP) systems are complete, integrated platforms, either on-premises or in the cloud, managing all aspects of a production-based or distribution business. ERP systems support all aspects of financial management, human resources, supply chain management, and manufacturing with your core accounting function.



ERP systems history



ERP vendors

odoo · Microsoft Dynamics 365 · ORACLE · EPICOR · sage · infor · IFS · Deltek · QAD · SAP · Acumatica · workday.

ERP systems for circular business models

Sustainable ERPs - an enterprise system that incorporates the key elements of the corporate sustainable value chain into a centralised system.


JOURNAL of BUSINESS ECONOMICS & MANAGEMENT

MORE THAN REPORTING: ENTERPRISE RESOURCE PLANNING AS ENABLER OF BUSINESS MODEL TRANSFORMATION FOR CLIMATE CHANGE MITIGATION

Dimension	Categories	Number of patents
Production optimisation	Waste/resources reduction	49
	Improved efficiency	46
	Digitalised operations	13
	Production planning and forecasting	8
Sustainability management and monitoring	Emission management, monitoring, and disclosure	6
	Traceability, transparency, and certification	6
	Improved data accuracy	5
	Energy consumption monitoring	1
Supply chain performance	Warehouse efficiency improvement	7
	Logistics optimisation	5
	Supply chain management, resilience, and transparency	4
	Risk management	1

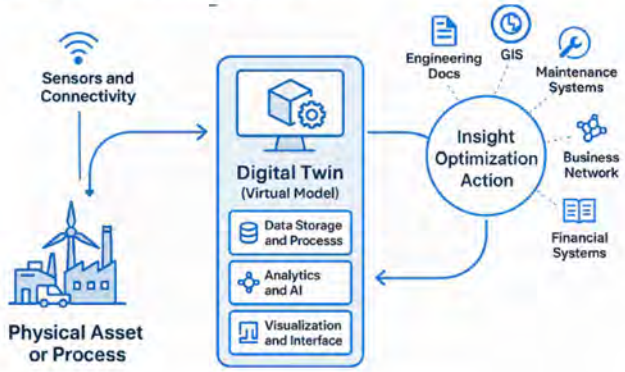
Digital twin

Definition: a digital twin is a virtual representation of a physical object or system that uses real-time data to accurately reflect its real-world counterpart's behavior, performance and conditions.

- Enable continuous monitoring, simulation and analysis of an object, product or system over the course of its lifecycle
- Allows real-time, two-way data exchange between the object and its virtual replica
- Provides insight into how an object functions in the present—and projecting how it might behave in future scenarios

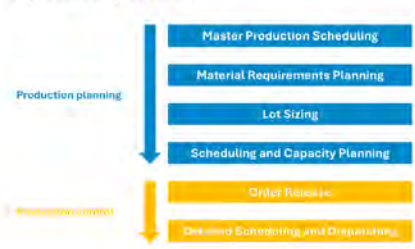


How digital twin work



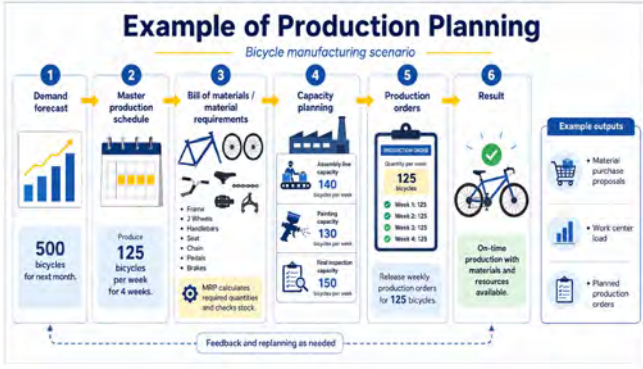
Production planning

Definition: Production planning is a core component of production management and one of the most important tasks in manufacturing companies. It deals with the long-, medium- and short-term planning of all production processes.





Production planning (example)



Financial accounting

Definition: Financial accounting is a systematic process used by businesses to track and report their financial performance and position through standardized financial statements.

The accounting and finance modules in an ERP system provide finance teams with the capabilities they need to centrally manage the financial aspects of an organization. These tools include standard accounting functionality, such as reporting, accounts payable and expenses, accounts receivables and cash management, and revenue recognition. ERP also can provide advanced capabilities, such as budgeting, forecasting, and order processing.



Cost controlling

Definition: Cost control is the process of identifying, eliminating or reducing unnecessary business expenses in order to increase profits. Cost control starts with the budgeting process and looks at vendor selection and negotiation, leveraging early payment and volume discounts, using spend management systems, and improving manufacturing or construction efficiency and product quality.



Case study

A company receives an order for a bicycle and must plan, produce, record, and evaluate the product using an ERP system.

The case study connects ERP with the staff week theme **"Digital Twins for a Circular Future"** by focusing on three perspectives:

Production Planning: building the operational twin
What materials are needed?
How is the production order created and released?

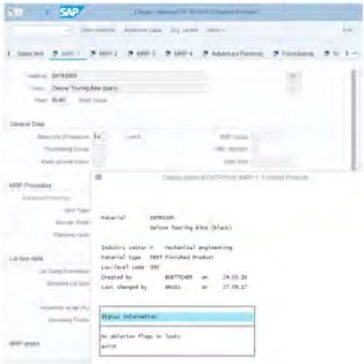
Financial Accounting: recording the financial impact
How are purchases, inventory movements, production activities, and sales recorded?
How do these transactions affect inventory, accounts payable, revenue, and financial statements?

Cost Controlling: supporting circular decisions
How much does the bicycle cost to produce?
Which materials and activities create the main costs?
How can ERP data support lifecycle cost analysis, repair, reuse, and resource efficiency?

Case study

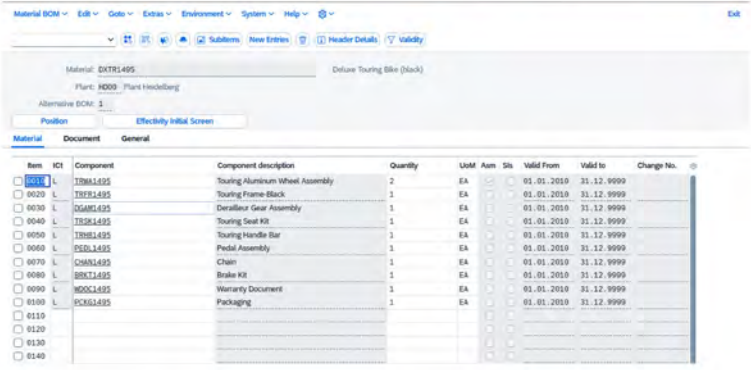


Designing a new product (a bicycle)



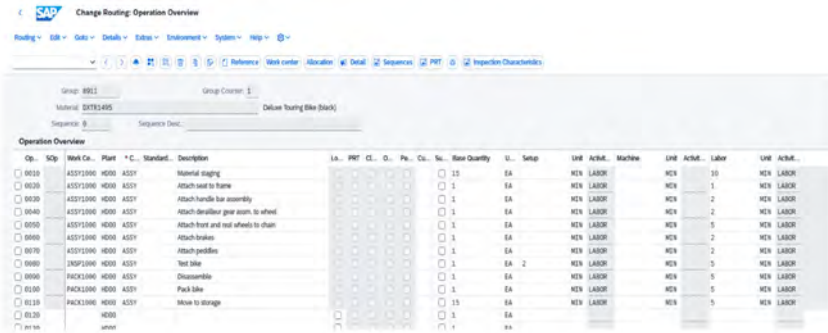


Creating the Bill of Materials (BOM)



Item	ICI	Component	Component description	Quantity	UoM	Asm	Sls	Valid From	Valid to	Change No.
0010	L	TRWA1495	Touring Aluminum Wheel Assembly	2	EA			01.01.2010	31.12.9999	
0020	L	TRFR1495	Touring Frame-Black	1	EA			01.01.2010	31.12.9999	
0030	L	DGAM1495	Derailleur Gear Assembly	1	EA			01.01.2010	31.12.9999	
0040	L	TRSK1495	Touring Seat Kit	1	EA			01.01.2010	31.12.9999	
0050	L	TRHB1495	Touring Handle Bar	1	EA			01.01.2010	31.12.9999	
0060	L	PEDL1495	Pedal Assembly	1	EA			01.01.2010	31.12.9999	
0070	L	CHAN1495	Chain	1	EA			01.01.2010	31.12.9999	
0080	L	BRKT1495	Brake Kit	1	EA			01.01.2010	31.12.9999	
0090	L	WDOC1495	Warranty Document	1	EA			01.01.2010	31.12.9999	
0100	L	PCKG1495	Packaging	1	EA			01.01.2010	31.12.9999	
0110										
0120										
0130										
0140										

Defining the routing



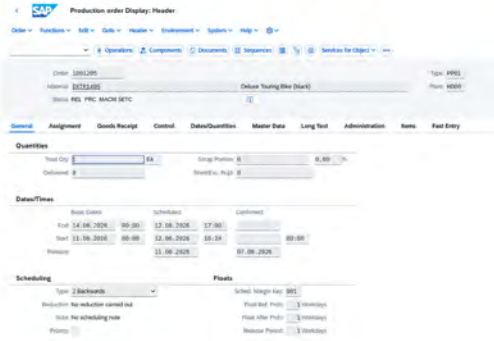
Create a production version (BOM + routing)



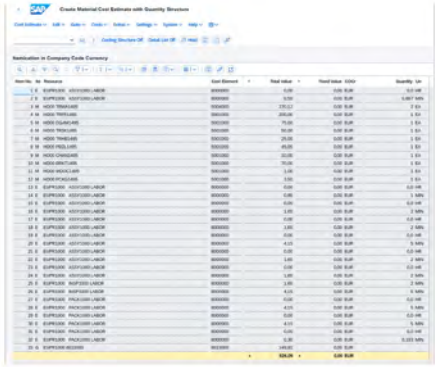
Building the ERP-based digital representation of the bicycle

01	Material master	• Defines the product
02	Bill of Materials	• Defines the components
03	Routing	• Defines the production process
04	Production version	• Connects the product structure (components) with the process (activities)

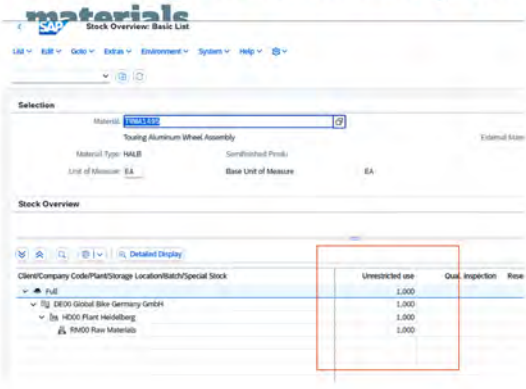
Creating a production order



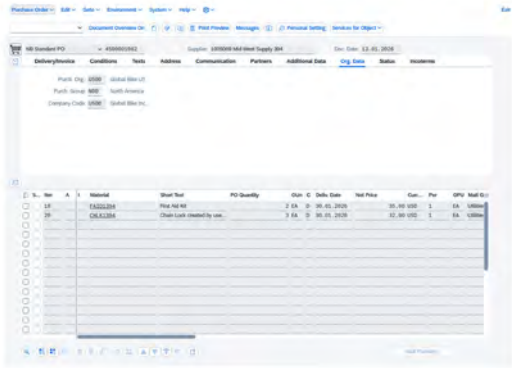
Create cost estimates



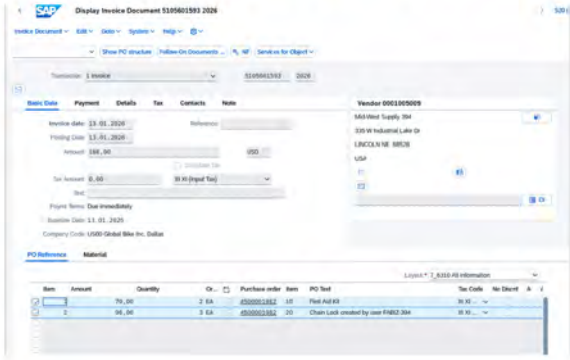
Checking the availability of the raw materials



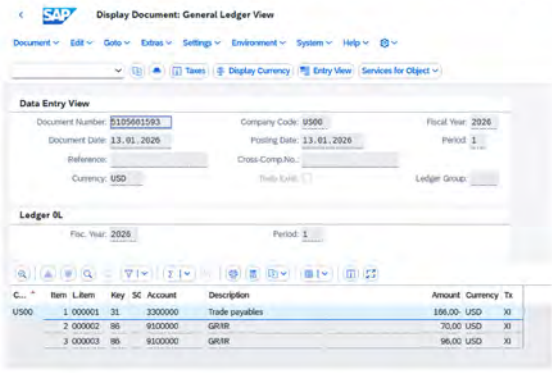
Buying raw materials for the bicycle



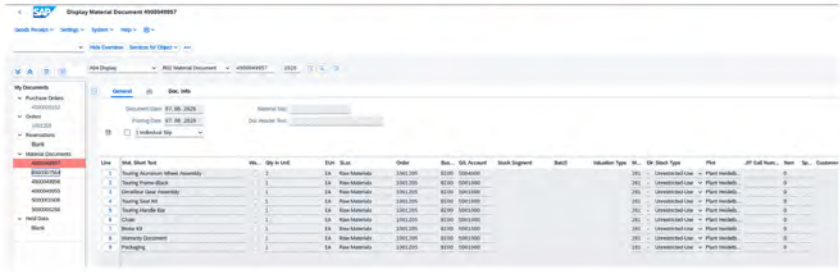
Buying raw materials for the bicycle (cont.)



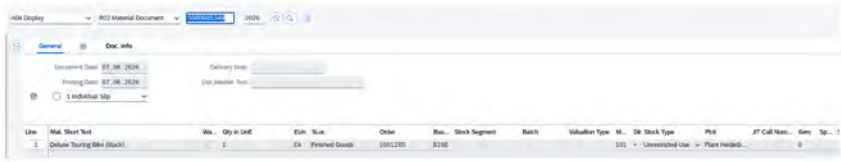
Buying raw materials for the bicycle (cont.)



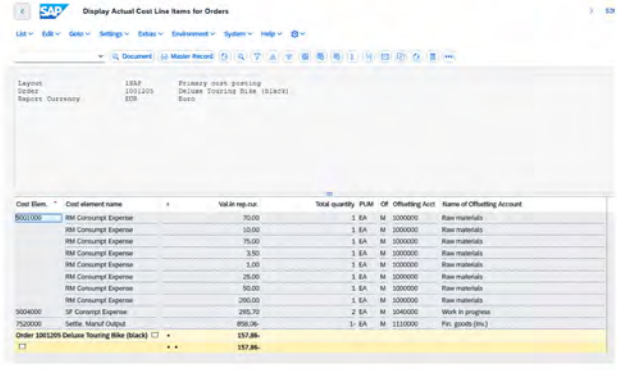
Using the raw materials for production



Recording the new entry of the bicycle



Check the actual cost of the finished goods



From physical movement to financial impact



Reflection questions:



DEVELOPMENT INITIATIVES CARRIED OUT BY BUSINESSES TO PROMOTE THE CIRCULAR ECONOMY: EVIDENCE FROM EMPLOYEE PERCEPTIONS

Prof. AH dr hab. inż. Teresa Kupczyk
Humanitas University, Poland

Abstract: *This study examines the extent to which enterprises undertake development initiatives that support the transition to a circular economy. Drawing on a quantitative questionnaire survey of 767 employees, the analysis combines a critical review of the literature with statistical examination of employee assessments. The findings indicate a generally low level of organisational engagement in this area, with a mean score of 2.36 on a five-point scale. In 35% of the enterprises surveyed, no circular economy-related initiatives were identified; in 18%, such initiatives were reported only occasionally; and only 2% of organisations were found to pursue them strategically. No statistically significant gender differences were observed, whereas younger respondents reported a greater prevalence of such initiatives in their organisations. Pearson's correlation analysis further shows that more frequent implementation of circular economy-related initiatives is positively associated with Smart Factory solutions, Industry 4.0-oriented activities and digital competence development, as well as with more favourable evaluations of leadership and change management in digital transformation. Higher levels of such activity are also associated with stronger employee motivation, greater participation in social and environmental initiatives, more active engagement in the co-creation of processes and standards aligned with CSR principles, broader competence development, a stronger feedback and dialogue culture, and greater support for work–life balance. By contrast, lower levels of engagement are linked to employee perceptions of insufficient managerial initiative, competences and strategic orientation in this domain. The study contributes to the emerging literature on organisational conditions for circular economy implementation by highlighting the developmental, managerial and cultural factors associated with enterprise-level engagement.*

Keywords: *circular economy, corporate social responsibility, digital transformation, employee perceptions*

AKADEMIA HUMANITAS

7th International Conference on Governance and Strategic Management (ICGSM)
"Digital Twins for a Circular Future"
June 11-13, Burgas 2026

Development Initiatives Carried out by Businesses to Promote the Circular Economy: Evidence from Employee Perceptions

Teresa Kupczyk, Humanitas University
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Poland





CZŁOWIEK. To się liczy

The plan of the presentation



1. Justification for undertaking the research
2. Objectives of the research
3. Research questions and hypotheses
4. Terminology
5. Research methods and research sample
6. Selected research findings
7. Selected research conclusions

AKADEMIA HUMANITAS

CZŁOWIEK. To się liczy

Justification for conducting the research and its objectives



- The justification for conducting this research was the fact that,
  - Circular material use rate in Poland stands at around 7.7%, which places our country below the European Union average of 12.2% (in 2010, this rate was in Poland 11.1%).

Sources: Circular material use rate in Europe Published 28 Nov 2025, https://www.eea.europa.eu/en/analysis/indicators/circular-material-use-rate-in-europe

  - It is therefore essential to improve the situation and introduce measures to promote the circular economy, particularly by businesses.

- The aim of my research was to identify the development initiatives undertaken by businesses to promote the circular economy.

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CZŁOWIEK. To się liczy

Research questions and theses



The research conducted was aimed at finding answers to the research problems posed, which took the form of the following questions:

- Are companies undertaking initiatives to promote the circular economy?
- What is the level of these initiatives in the opinion of employees?
- Are there significant differences in this regard when taking gender and age into account?
- Are there significant correlations between the implementation of circular economy initiatives and the implementation of 'Smart Factory' solutions, Industry 4.0, the development of digital skills, employee motivation, as well as more positive assessments of leadership and change management within the context of digital transformation?

In my research, I put forward the following thesis:

In the opinion of the employees, the company is not doing enough to promote the circular economy, and managers lack the necessary competence and strategic vision in this regard.

Terminology



- In my research, the **Circular economy** was defined as an economic model where the value of materials is maximised and maintained for as long as possible; the input of materials and their consumption is minimised; and the generation of waste is prevented and negative environmental impacts reduced throughout the life-cycle of materials.
- The **Circular economy** is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.
- This model provides for a transition from **a linear model** (production – consumption – disposal) to a **circular model**, in which waste, where it is generated, becomes a raw material.

Source: https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits

Research methodology, sample and data analysis



In order to address the research problem and test the hypotheses, I conducted quantitative and qualitative empirical research based on a questionnaire survey of a sample of **767 company employees**.

- I used purposive sampling.
- Respondents assessed the level of development activities carried out by companies in support of the circular economy on a scale of 1 to 5, where: 1 – no development activities at all, 2 – sporadic, 3 – development activities of moderate scope, 4 – development activities of significant scope, 5 – implemented strategically
- Relationships between categorical variables were examined using the chi-square test.
- To analyse relationships between numerical and categorical variables, the Mann-Whitney U test (for two populations) or the Kruskal-Wallis test (for more than two populations) was used.
- For two numerical variables, Spearman's rank correlation coefficient was used.

- The results indicate a generally low level of organisational engagement in initiatives aimed at implementing solutions that support the 'circular economy'; the average score was 2.36 on a five-point scale.
- In 35% of the enterprises surveyed, no circular economy-related initiatives were identified; in 18%, such initiatives were reported only occasionally; and only 2% of organisations were found to pursue them strategically.



Selected research findings

Table 1. Answers to the question: "To what extent does your organisation implement development initiatives in support of the 'circular economy'"? (N=767)

		In total	Gender		Age			
			woman	man	1950-1979	1980-1989	1990-1999	od 2000
		% of N	% of N	% of N	% of N	% of N	% of N	% of N
Circular economy	no development activities at all	35,2%	37,5%	32,0%	51,9%	34,0%	34,2%	19,4%
	sporadic development activities of moderate scope	17,5%	18,0%	16,8%	17,0%	22,6%	16,3%	13,9%
	development activities of significant scope	27,6%	26,8%	28,8%	21,7%	25,8%	28,1%	37,5%
	implemented strategically	15,5%	14,2%	17,4%	5,7%	15,7%	16,3%	25,0%
	In total	4,2%	3,5%	5,1%	3,8%	1,9%	5,1%	4,2%
		100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%

Source: own research

Selected research findings



- No statistically significant differences were observed between the genders in terms of their views on the initiatives being carried out to promote the circular economy.
- Younger respondents noted a greater number of initiatives within their organisations aimed at promoting the circular economy.

Table 2. Answers to the question: "To what extent does your organisation implement development initiatives in support of the 'circular economy"? (N=767). Differences in responses between women and men, as well as between people of different ages.

Test chi-kwadrat Pearsona				
		In total	Gender	Age
Circular economy	Chi-kwadrat		4,274	35,031
	df		4	12
	Statistical significance		0,370	,000*

* The chi-squared statistic is significant at the ,05

Source: own research

Table 3. Statistically significant correlations between the implementation of circular economy initiatives and activities relating to 'Smart Factory', Industry 4.0, the development of digital skills, as well as assessments of leadership and change management within the context of digital transformation (N=767).

Variables	Pearson's correlation
Smart Factory	0,689
Digital skills	0,592
Industry 4.0	0,562
How would you rate the leadership/management of change in the context of digital transformation?	0,395
To what extent do you feel motivated to work by the incentive scheme in place within the organisation?	0,319
Involving employees in social and environmental initiatives (social engagement programmes)	0,274
Task forces/project teams/innovation teams	0,265
Involving employees in the development of processes and standards in line with CSR principles	0,264
Development of non-vocational skills (sports activities, hobbies)	0,264
Promoting a culture of rapid feedback and dialogue	0,256
Promoting work-life balance	0,254
Committees representing employees' interests	0,254
Training courses on social responsibility, environmental protection and sustainable development	0,243
Improving the skills of local residents	0,236
Talent development programmes	0,234
Flexible forms of employment	0,228
Assessment/Development Center	0,215
Promoting an organisational culture based on a family-friendly workplace	0,212
Brak inicjatywy, kompetencji i strategii ze strony kadry kierowniczej	-0,225



Selected research findings

Source: own research

Selected research conclusions



- Pearson's correlation analysis further shows that more frequent implementation of circular economy-related initiatives is positively associated with: Smart Factory solutions, Industry 4.0-oriented activities and digital competence development, as well as with more favourable evaluations of leadership and change management in digital transformation.

- Higher levels of such activity are also associated with stronger employee motivation, greater participation in social and environmental initiatives, more active engagement in the co-creation of processes and standards aligned with CSR principles, broader competence development, a stronger feedback and dialogue culture, and greater support for work–life balance.

- By contrast, the less frequently an organisation undertakes development initiatives relating to the circular economy, the more often employees point to a lack of initiative, competence and strategy among managers in this area.

Selected research conclusions



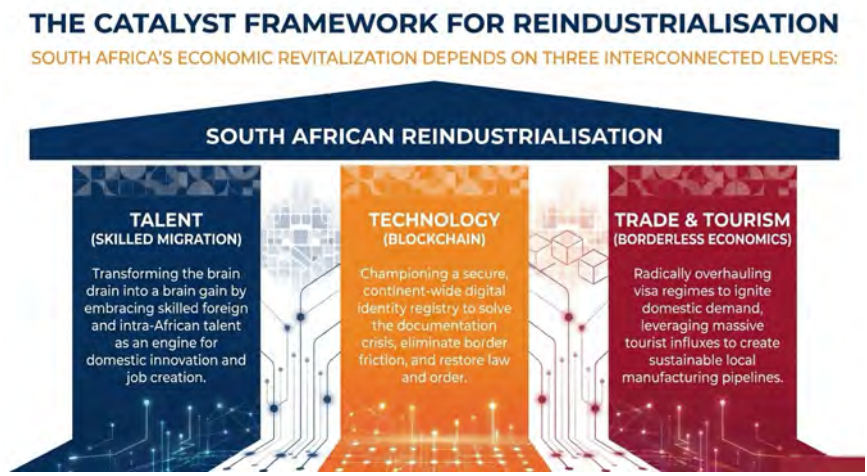
- The hypothesis that, in the view of the company's employees, the organisation is not taking sufficient action to promote the circular economy, and that management lacks the necessary competences and strategic vision in this area, has been confirmed.

- There is therefore a clear need for much more extensive development initiatives with in businesses to promote the circular economy, and for these initiatives to be treated as a strategic priority.

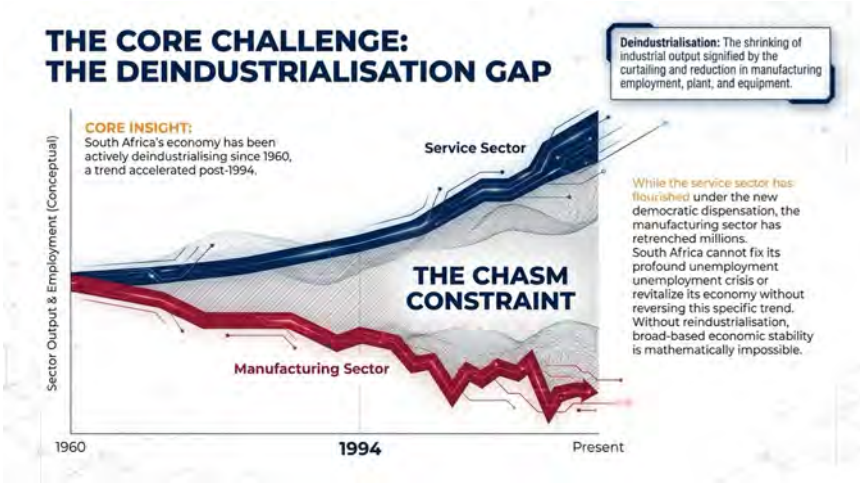
- The circular economy is not only a necessity, but also an opportunity to increase resource independence and make more efficient use of available resources.

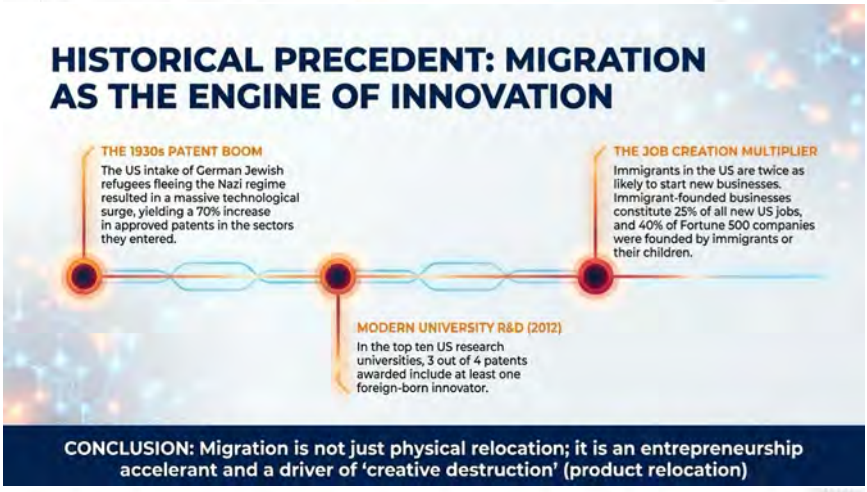
POTENTIAL ROLE OF THE BLOCKCHAIN TECHNOLOGY TO REINDUSTRIALISE THE SOUTH AFRICAN ECONOMY

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Graduate School of Business leadership (SBL), University of South Africa (UNISA)









A TALE OF TWO POLICIES: THAILAND VS. GHANA

	THAILAND	GHANA
THE 1963 BASELINE	**Agrarian focus (Rice).** Comparable land size and economy to Ghana.	**Agrarian focus (Cocoa).** Comparable land size and economy to Thailand.
SKILLED MIGRATION POLICY	**Radically open.** Embraced foreign technical skills and prioritized domestic production, regardless of the producer's origin.	**Highly restrictive.** Blocked skilled migration and strictly protected local labor pools.
MODERN ECONOMIC OUTCOME	Economy is now **10x larger** than Ghana's. Rapid industrial growth transformed the nation into a hub for and motor vehicle manufacturing.	Stagnant industrial growth; economy remains fundamentally constrained by its restrictive historical baseline.

POLICY RECOMMENDATION 1: OPEN DOORS FOR TALENT

EASE LABOR RIGIDITIES
Radically simplify visa renewals, fast-track permanent residency, and reduce bureaucratic barriers to business creation for foreign entrepreneurs.

ABOLISH ARTIFICIAL LIMITS
Eliminate or vastly expand the "critical skills list" to attract a much broader range of specialized workers and fresh technical expertise.

SADC INTEGRATION
Allow immediate free movement for individuals from the Southern African Development Community (SADC) to accelerate regional skills exchange.

THE EMPOWERMENT CAVEAT

Do not abandon affirmative action. Instead, **weaponize imported skilled labor.** The most practical empowerment strategy is to **mandate that imported skilled workers provide direct, on-the-job training** for historically and currently disadvantaged South Africans.

DECONSTRUCTING XENOPHOBIA: MYTH VS. ECONOMIC REALITY

THE PERCEPTION	THE ECONOMIC REALITY
Myth: Foreigners **steal local jobs**.	**Reality: SADC labor** sustains essential industries. South Africans often eschew roles like underground drilling (filled by Lesotho/Mozambique nationals) or hospitality. Expelling them would collapse operations, hike operational expenses, and pass severe costs to local consumers.
Myth: Foreigners **dominate academic** and **state institutions**.	**Reality:** South Africa faces a dire **domestic skills shortage**. Locals increasingly bypass PhDs for lucrative private-sector jobs. Foreign nationals fundamentally sustain critical **R&D** (HSRC, CSIR, NRF, TIA, Mintek) and higher education.
Myth: Foreigners are a distinctly **different people**.	**Reality:** The **Bantu Migration** (spanning 5,000 years) means most black South Africans share direct ancestry, DNA, and **cultural ties** with SADC nations. Traditional free movement existed long before apartheid borders were erected in 1948.

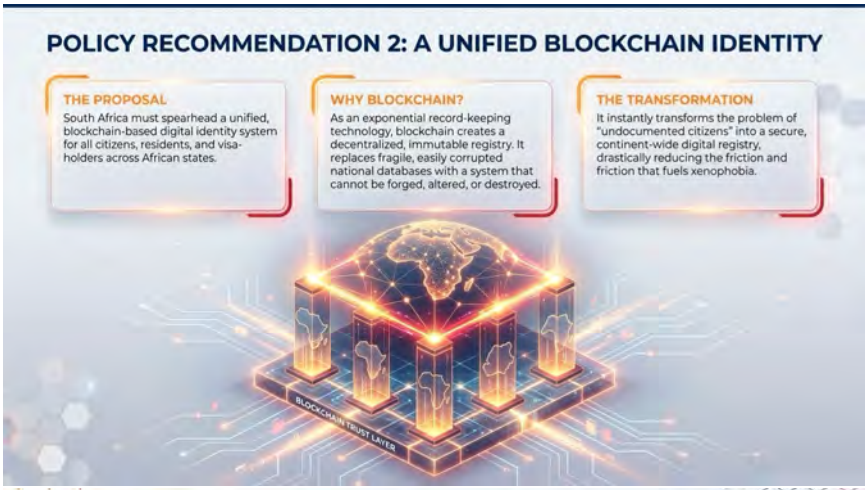
THE ROOT OF THE FRICTION: THE DOCUMENTATION CRISIS

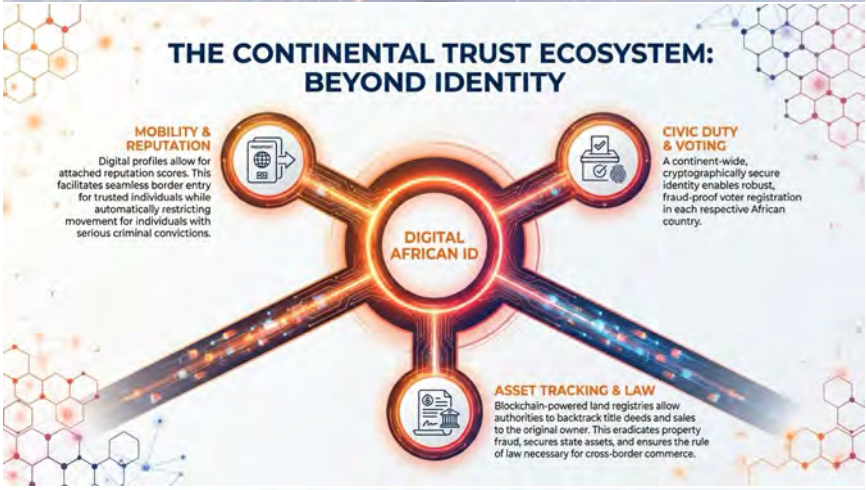


THE CATALYST FOR CONFLICT
While xenophobic violence is unjustifiable, it is fueled by a genuine administrative failure. Since 1994, border fences have fallen into disrepair and SANDF patrols have been reallocated.

THE UNDOCUMENTED REALITY
Unpatrolled borders have created a massive population of undocumented individuals. This makes it impossible to trace criminals, maintain law and order, or subject offenders to the South African justice system.

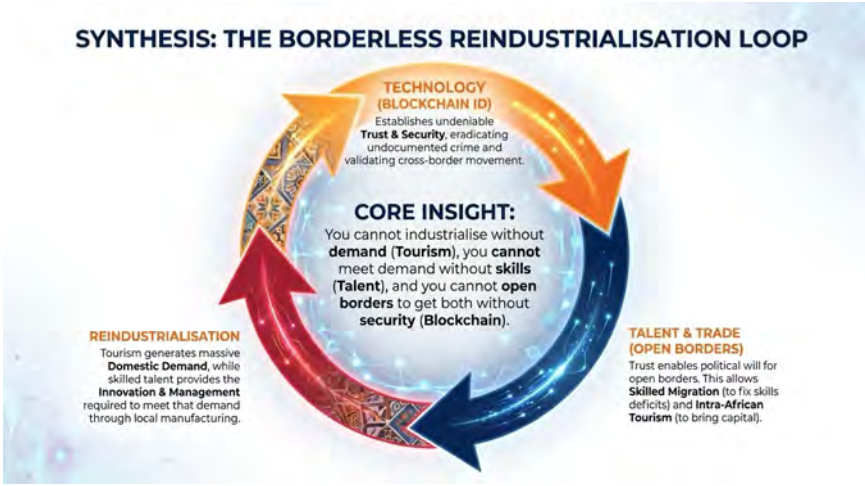
THE PIVOT
You cannot reindustrialise a chaotic system. The solution is not to rebuild physical apartheid-era fences, but to build an unbreakable digital perimeter.


POLICY RECOMMENDATION 2: A UNIFIED BLOCKCHAIN IDENTITY
THE PROPOSAL
South Africa must spearhead a unified, blockchain-based digital identity system for all citizens, residents, and visa-holders across African states.
WHY BLOCKCHAIN?
As an exponential record-keeping technology, blockchain creates a decentralized, immutable registry. It replaces fragile, easily corrupted national databases with a system that cannot be forged, altered, or destroyed.
THE TRANSFORMATION
It instantly transforms the problem of "undocumented citizens" into a secure, continent-wide digital registry, drastically reducing the friction and friction that fuels xenophobia.
BLOCKCHAIN TRUST LAYER


THE CONTINENTAL TRUST ECOSYSTEM: BEYOND IDENTITY
MOBILITY & REPUTATION
Digital profiles allow for attached reputation scores. This facilitates seamless border entry for trusted individuals while automatically restricting movement for individuals with serious criminal convictions.
CIVIC DUTY & VOTING
A continent-wide, cryptographically secure identity enables robust, fraud-proof voter registration in each respective African country.
DIGITAL AFRICAN ID
ASSET TRACKING & LAW
Blockchain-powered land registries allow authorities to backtrack title deeds and sales to the original owner. This eradicates property fraud, secures state assets, and ensures the rule of law necessary for cross-border commerce.


POLICY RECOMMENDATION 3: UNLEASHING TOURISM AS A CATALYST
THE MISSED OPPORTUNITY
Prior to COVID-19, SA received 10.2M tourists, but only 2.4M overseas high-value visitors. Thailand attracts 32M annually. Tourism is SA's 2nd largest sector (8.6% GDP, 1.5M jobs), yet it is suffocating.
KRUGER NATIONAL PARK
CRADLE OF HUMANKIND
BUREAUCRATIC CHOKEPOINTS
• Visa Failures: E-visa rollouts were delayed 3 years and restricted to just 14 countries, bleeding US$ billions compared to New Zealand or Thailand.
• Infrastructure Collapse: Crucial Durban beaches were closed during peak seasons (2022/2023) due to severe E. coli sewage contamination, losing billions of Rands.
DURBAN BEACHES
THE FIX
Emulate Namibia. Grant 90-day visas on arrival to drastically lower friction and treat foreign visitors as informal global ambassadors.
CAPE TOWN


THE TOURISM-TO-MANUFACTURING PIPELINE
STEP 1: THE DOMESTIC CONSTRAINT
South Africa's domestic market is too small to independently support mass manufacturing (unlike China, the EU, or the US).
OPEN BORDERS
STEP 2: THE INFLUX TRIGGER
Streamlined visas and open borders create a massive influx of international tourists with foreign currency.
FOREIGN FOOT TRAFFIC
STEP 3: THE MULTIPLIER EFFECT
Increased tourism creates enormous, immediate domestic demand for locally manufactured goods.
DOMESTIC DEMAND
PROOF OF CONCEPT: Car rental companies, heavily patronized by tourists, purchase over 12.5% of all vehicles assembled in South Africa. More tourists = more cars manufactured = reindustrialisation.


SYNTHESIS: THE BORDERLESS REINDUSTRIALISATION LOOP
TECHNOLOGY (BLOCKCHAIN ID)
Establishes undeniable Trust & Security, eradicating undocumented crime and validating cross-border movement.
CORE INSIGHT:
You cannot industrialise without demand (Tourism), you cannot meet demand without skills (Talent), and you cannot open borders to get both without security (Blockchain).
REINDUSTRIALISATION
Tourism generates massive Domestic Demand, while skilled talent provides the Innovation & Management required to meet that demand through local manufacturing.
TALENT & TRADE (OPEN BORDERS)
Trust enables political will for open borders. This allows Skilled Migration (to fix skills deficits) and Intra-African Tourism (to bring capital).

GENERAL SESSION

DIGITAL TWINS AS A FACTOR FOR THE TRANSFORMATION OF EDUCATIONAL ECOSYSTEMS FOR A SUSTAINABLE FUTURE

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Burgas Free University

Abstract: *Contemporary digital transformation guides the development of educational systems toward the establishment of intelligent, adaptive, and sustainable educational ecosystems. Digital twins are increasingly recognized as a technological tool with broad application in modeling, analyzing, and optimizing the learning process in real time. The present study examines the significance of digital twins as a factor in the transformation of educational ecosystems within the context of Education 5.0 and sustainable development.*

The research focus is directed toward the integration of artificial intelligence, learning analytics, personalized learning, and STEM/STEAM approaches in the development of intelligent educational environments. Particular attention is given to the pedagogical and psychological dimensions of the digital environment associated with learners' motivation, adaptability, engagement, and digital well-being throughout the learning process.

The study develops a conceptual model of a sustainable educational ecosystem based on the interaction between digital twins, innovative pedagogical practices, and data-driven management of educational processes. The analysis also addresses issues related to data protection, ethical dimensions, and the development of an inclusive digital educational environment.

The findings highlight the role of digital twins as a strategic resource for the development of sustainable, personalized, and future-oriented education, supporting the effective management and continuous enhancement of the learning process in accordance with the dynamics of the digital society.

Keywords: *digital twins, educational ecosystems, sustainable education, Education 5.0, educational transformation, STEM/STEAM education, artificial intelligence, learning analytics, learning process, digital pedagogy*

Introduction

The digital transformation of contemporary society creates conditions for the dynamic development of educational systems and directs pedagogical practices toward the establishment of intelligent, adaptive, and

sustainable educational ecosystems. The advancement of digital technologies, artificial intelligence, learning analytics, and intelligent data management systems expands the opportunities for enhancing the learning process and for creating educational environments oriented toward individual needs, motivation, and the active participation of learners.

Within the framework of Education 5.0, technological solutions that support the personalization of the learning process, the adaptive management of educational resources, and the sustainable development of educational institutions are gaining increasing importance. Among the emerging innovative technologies, digital twins have attracted particular attention due to their potential for modeling, simulating, and analyzing processes and systems in real time. Initially developed and applied in industrial and engineering contexts, digital twins have gradually expanded their application to the educational domain through the creation of intelligent representations of learners, learning environments, and educational processes.

The integration of digital twins into educational settings supports the development of innovative pedagogical approaches based on data analytics, adaptive learning, and intelligent feedback. Such technological solutions create opportunities to enhance learner engagement, participation, and motivation, while simultaneously improving the management and organization of the learning process. At the same time, they contribute to the development of sustainable educational ecosystems in which the interaction between technology, pedagogical practices, and human factors supports the creation of inclusive, effective, and future-oriented digital learning environments.

Contemporary educational trends also emphasize the psychological dimensions of digital environments, including adaptability, digital well-being, social interaction, and learners' emotional engagement. From this perspective, digital twins are increasingly viewed as a valuable resource for designing more flexible and personalized learning processes that are aligned with learners' individual characteristics, developmental trajectories, and educational needs.

The relevance of the present study stems from the growing interest in intelligent educational technologies and their contribution to the sustainable development of educational ecosystems. The development of models for integrating digital twins into the learning process opens new opportunities for creating innovative educational environments based on the interaction between technology, pedagogy, and sustainable practices.

The aim of this study is to examine the role of digital twins as a factor in the transformation of educational ecosystems and to develop a

conceptual model for a sustainable digital educational environment that supports the effective management and continuous improvement of the learning process.

1. Theoretical Framework

1.1. Digital Twins and the Digital Transformation of Education

Digital transformation in education is associated with the integration of intelligent technologies that support the development of adaptive, personalized, and sustainable learning environments. Contemporary educational models increasingly direct the learning process toward active interaction among learners, educators, and digital technologies, emphasizing flexibility, innovation, and the development of key competencies.

M. Aleksieva conceptualizes digital transformation as a strategic process related to the modernization of educational environments and the development of innovative pedagogical practices oriented toward learners and the dynamics of contemporary society (Aleksieva, 2024). According to Ir. Mishkova-Yotova, intelligent educational technologies create opportunities for enhancing the learning process through the implementation of interactive and adaptive approaches aimed at increasing learners' motivation and engagement (Mishkova-Yotova, 2024).

Zl. Dimitrova views the educational ecosystem as a dynamic environment of interaction among educational institutions, technologies, pedagogical practices, and social factors directed toward the development of a sustainable and inclusive learning process (Dimitrova, 2022). According to the author, the development of an intelligent educational ecosystem supports the creation of an innovative environment characterized by collaboration, adaptability, and sustainability.

Research conducted by M. Baltov highlights the significance of sustainable development and the circular economy as factors contributing to the establishment of intelligent and sustainable social and educational systems (Baltov, 2023). The exploration of sustainable management models and resource efficiency creates opportunities for the development of educational ecosystems based on innovation, digitalization, and long-term sustainability. From this perspective, digital transformation is interpreted as a process that combines technological advancement, organizational adaptability, and sustainable management of educational environments.

The concept of digital twins has evolved rapidly within the context of intelligent technologies and data management. Michael Grieves (2014) defines a digital twin as a virtual representation of a real object, system, or process that enables real-time monitoring, analysis, and optimization.

Subsequently, the application of digital twins expanded beyond industrial environments and found relevance in healthcare, smart city management, and education.

According to Tao Fei (2019), digital twins provide opportunities for integrating physical and virtual environments through the use of data, simulations, and intelligent algorithms. Such an approach facilitates the development of adaptive systems capable of supporting analysis, prediction, and management processes.

In educational contexts, digital twins are associated with the development of intelligent models of learners, learning environments, and educational processes. John Curtis (2021) considers digital twins a tool for personalizing the learning process through the analysis of learner behavior, educational progress, and individual characteristics. This approach creates opportunities for establishing learning environments that recognize differences in learning pace, cognitive needs, and personal development among learners.

The development of the digital twin concept in education has directed attention toward the creation of virtual representations of learners that integrate information related to academic performance, cognitive activity, learning styles, motivation, and participation in educational activities. In this way, the digital twin provides a comprehensive picture of individual development and supports data-informed pedagogical decision-making. Such models expand the possibilities for designing individualized educational strategies, planning differentiated learning activities, and constructing adaptive learning scenarios tailored to learners' characteristics.

The practical application of a digital twin can be illustrated through mathematics education in primary school. During the completion of tasks in a digital learning environment, data are collected regarding problem-solving time, errors made, strategies applied, and the learner's level of independence. This information forms a dynamic educational profile that enables continuous monitoring of individual progress and the identification of areas requiring additional support. Based on these data, teachers can plan differentiated activities, provide additional exercises for consolidating specific knowledge and skills, or guide learners toward more advanced levels of complexity when sustained achievement is demonstrated.

The significance of digital twins increases within the framework of Education 5.0, where technologies are viewed as instruments for creating more human-centered, inclusive, and learner-oriented educational experiences. From this perspective, the digital twin functions as a connecting mechanism between data, pedagogical practices, and learner development,

supporting the establishment of intelligent learning environments characterized by high levels of adaptability and personalization.

Klaus Schwab (2016) associates the development of intelligent technologies with the processes of the Fourth Industrial Revolution, which are transforming the relationships among technology, society, and education. Changes in social and technological environments create new demands on educational institutions related to the development of digital competencies, data literacy, and readiness for lifelong learning. Within this context, digital twins are gradually becoming part of the contemporary digital infrastructure supporting the development of intelligent and sustainable educational ecosystems.

The integration of artificial intelligence, learning analytics, and adaptive educational systems further expands the possibilities for analyzing and managing the learning process. Through the collection and interpretation of data concerning learner activity, achievement, and educational behavior, opportunities emerge for the timely identification of learning needs, the provision of personalized support, and the enhancement of pedagogical strategies. Analytical technologies support not only the monitoring of educational progress but also the prediction of developmental trends, thereby extending the possibilities for planning and managing educational processes.

The application of digital twins is particularly promising in STEM education. For example, in a project dedicated to environmental protection and waste separation, learners may collect, analyze, and visualize data related to resource consumption within the school environment. The digital twin monitors each learner's participation, the development of inquiry skills, engagement in project activities, and achieved outcomes. The resulting information supports teachers in evaluating individual contributions and planning subsequent educational activities aimed at sustainable development, critical thinking, and practical problem-solving.

As a result, digital twins are emerging as an innovative tool for the development of contemporary educational environments in which technological solutions, pedagogical practices, and analytical mechanisms operate in a state of mutual interconnectedness. Their implementation creates conditions for the establishment of sustainable educational ecosystems characterized by adaptability, efficiency, inclusion, and the continuous improvement of the learning process.

1.2. Digital Twins in the Context of Intelligent School Environments and Primary Education

The advancement of digital transformation in education extends the application of intelligent technologies beyond higher education into school environments, including primary education. Contemporary educational policies and pedagogical practices increasingly emphasize the development of adaptive, inclusive, and technology-enhanced learning environments that support the acquisition of key competencies from the earliest stages of the learning process.

M. Aleksieva conceptualizes digital transformation as a process encompassing not only the technological dimensions of education but also changes in pedagogical interactions, educational models, and organizational environments (Aleksieva, 2024). Within this framework, intelligent technologies are associated with the development of personalized and flexible educational practices oriented toward learners' needs and active participation. In primary education, this is reflected in the adaptation of learning tasks to individual learning pace, the use of diverse digital resources, and the creation of personalized learning pathways that support the development of each child.

At the primary education level, the digital environment plays a significant role in fostering cognitive engagement, motivation, and fundamental digital competencies. Zl. Dimitrova defines the educational ecosystem as a space of interaction among technologies, pedagogical approaches, and the social environment that supports the development of a sustainable and inclusive learning process (Dimitrova, 2022). According to the author, the integration of digital resources creates opportunities for increasing learner participation and for developing interactive forms of learning. A practical example of this approach can be found in language and literacy education, where learners engage with digital books, interactive exercises, and multimedia resources that simultaneously develop reading literacy, communication skills, and media literacy.

Within primary education, digital twins can be viewed as tools for modeling and monitoring individual educational progress, learning activity, and competency development. Michael Grieves (2014) defines digital twins as virtual models that reflect the characteristics and behavior of real systems and processes. In school environments, this approach enables the creation of dynamic learner profiles that are continuously updated throughout the learning process and support data-informed pedagogical decision-making.

The relationship between digital twins and personalized learning becomes particularly evident in mathematics education. When a learner is developing addition and subtraction skills within the number range up to twenty, the digital twin may collect information regarding task completion time, error frequency, problem-solving strategies, and the degree of independent work. These data facilitate the identification of specific educational needs. For instance, when a learner demonstrates strong performance in tasks supported by visual representations while requiring additional support with abstract numerical operations, the teacher may incorporate more visual models, manipulative materials, and practical learning situations. In this way, the concept of a learner-centered educational environment described by Aleksieva (2024) is translated into pedagogical practice.

The development of learning analytics and AI-based technologies creates opportunities for analyzing learning activity and adapting educational content to individual learning pace and preferences. George Siemens and Phil Long (2011) define learning analytics as an approach for interpreting educational data with the purpose of enhancing the learning process and improving educational effectiveness. In primary education, such mechanisms support the monitoring of educational development and contribute to more precise planning of pedagogical activities.

The application of digital twins is particularly valuable in the development of reading literacy. A digital twin can integrate information regarding reading fluency and accuracy, text comprehension, information extraction, inference-making, and participation in discussions related to textual content. If a learner demonstrates fluent reading skills while requiring additional support in interpreting meaning, the system identifies this characteristic and provides information that can guide the selection of activities aimed at improving reading comprehension. Similarly, a learner may demonstrate strong progress when working with narrative texts while benefiting from additional support when engaging with informational texts. Such information enables teachers to select appropriate reading materials, reading strategies, and analytical tasks tailored to individual learner development. In this context, the digital twin supports not only reading technique but also functional literacy, which represents a key educational priority in primary education.

Motivation, emotional engagement, and active participation in learning activities are particularly important during the primary education stage. Ir. Mishkova-Yotova considers gamification and interactive educational scenarios as effective means of stimulating cognitive engagement,

collaboration, and active learning (Mishkova-Yotova, 2024). From this perspective, digital twins and intelligent learning systems support the development of adaptive educational models aligned with the developmental characteristics of young learners.

The application of digital twins is especially promising in STEM education. In projects dedicated to waste separation, environmental protection, or the observation of natural phenomena, learners can collect data, conduct measurements, analyze results, and propose solutions to real-world problems. The digital twin monitors participation throughout each stage of the activity, including idea generation, information gathering, teamwork, interpretation of findings, and presentation of conclusions. The accumulated information provides opportunities for analyzing the development of critical thinking, communication, collaboration, and problem-solving skills. Such an approach corresponds with the work of Aleksieva, Kolarova, and Mishkova-Yotova, who view STE(A)M environments as spaces for fostering creativity, inquiry-based learning, and active participation in the learning process (Aleksieva, Kolarova & Mishkova-Yotova, 2024).

The potential of digital twins is also evident in monitoring learners' social and emotional development. Information related to participation in collaborative activities, peer communication, and engagement in group projects enables the identification of individual strengths and preferred forms of interaction. Such information supports the creation of a supportive learning environment and encourages the meaningful participation of all learners in the learning process.

The integration of digital twins into school environments is closely related to the development of sustainable educational ecosystems based on the interaction among technologies, pedagogical practices, and social factors. M. Baltov considers sustainable development and the principles of the circular economy as foundations for establishing intelligent systems characterized by efficiency, adaptability, and sustainable resource management (Baltov, 2023). In educational contexts, these principles support the development of intelligent school environments focused on the long-term development of competencies and responsible attitudes toward resources. Projects related to environmental protection, energy efficiency, or sustainable lifestyles provide opportunities for learners to apply knowledge in authentic situations, while digital twins support the monitoring of their progress and development.

Within this context, digital twins can be regarded as an integral component of the intelligent educational infrastructure of schools, supporting adaptability, personalization, and effective management of the learning

process in primary education. Through the integration of pedagogical practices, analytical technologies, and data related to learner development, digital twins create conditions for establishing sustainable educational ecosystems oriented toward quality education, active participation, and the holistic development of every child.

1.3. The Digital Twin as an Adaptive Learner Model in Primary Education

Within the context of the digital transformation of education, the concept of the digital twin acquires a new meaning associated with modeling the learner's individual educational profile. In educational settings, a digital twin can be understood as a dynamic system that integrates data related to learning activities, academic achievement, preferred learning strategies, and interaction patterns. Such an approach creates opportunities for a deeper understanding of individual learner development and for designing educational solutions tailored to the characteristics of each learner.

In primary education, the significance of such models is determined by the need for the learning process to accommodate the specific characteristics of child development, the diversity of cognitive styles, and varying levels of readiness for acquiring new knowledge and skills. From this perspective, the digital twin functions as an intelligent educational profile that provides up-to-date information about learner development and supports the planning of appropriate pedagogical interventions.

According to M. Aleksieva, the digital transformation of education requires a reconsideration of traditional learning models through the integration of intelligent technologies that place the learner at the center of the educational process (Aleksieva, 2024). In this context, the digital twin can be interpreted as a tool that enables the more precise alignment of educational content and learning activities with learners' individual progress and educational needs.

A key factor in the development of such models is the analysis of educational data. George Siemens views learning analytics as a means of extracting and interpreting information about learning behavior in order to improve the learning process and enhance educational effectiveness (Siemens & Long, 2011). Combined with digital twins, analytical technologies provide opportunities for monitoring educational progress and supporting informed pedagogical decisions based on real data concerning learner development.

Particularly important in primary education is the integration of STEM and STEAM approaches that encourage inquiry-based learning, creativity,

and the practical application of knowledge. Aleksieva, Kolarova, and Mishkova-Yotova emphasize that STE(A)M activities and game-based educational scenarios create conditions for stimulating creative thinking, collaboration, and active participation in the learning process (Aleksieva, Kolarova & Mishkova-Yotova, 2024).

Similarly, Ir. Mishkova-Yotova considers gamification a pedagogical approach that enriches the educational environment through the inclusion of interactive challenges and collaborative learning situations. According to the author, integrating game elements into the learning process creates opportunities for increasing engagement, initiative, and active participation among learners (Mishkova-Yotova, 2024).

From this perspective, the digital twin can support the development of individualized learning pathways aligned with learners' interests, activity levels, and achievements within STEM learning environments.

From the perspective of media and digital literacy, Zl. Dimitrova emphasizes the importance of developing learners' abilities to critically interpret, analyze, and utilize information in digital environments from the earliest years of schooling (Dimitrova, 2022). This perspective broadens the understanding of the digital twin's role, suggesting that it can support not only the monitoring of educational progress but also the development of competencies related to navigating and actively participating in contemporary information environments.

In this sense, the digital twin emerges as a component of the intelligent educational ecosystem that combines data analytics, pedagogical practices, and individualized support within the learning process. Its application in primary education creates opportunities for more precise planning of educational activities, more comprehensive monitoring of learner development, and the establishment of sustainable learning environments centered on children's needs.

1.4. Intelligent School Ecosystems and the Sustainable Development of the Learning Process

The development of intelligent school environments is associated with the establishment of educational ecosystems in which technological solutions, pedagogical interactions, and organizational mechanisms operate within conditions of interconnectedness and dynamic adaptability. Within this framework, the learning process is viewed as a system of continuous interactions among learners, teachers, digital resources, and analytical tools oriented toward sustainable development and enhanced educational effectiveness.

Zl. Dimitrova defines the educational ecosystem as an environment in which technological and social interactions support the development of sustainable pedagogical practices and inclusive learning models (Dimitrova, 2022). In primary education, such an environment is particularly important for the development of fundamental cognitive, communicative, and digital competencies, as well as for fostering active educational engagement.

An intelligent school ecosystem integrates adaptive technologies, digital resources, and analytical mechanisms that create conditions for structuring personalized learning pathways. Within this context, digital twins can function as mechanisms for synchronizing learners' individual educational profiles with the characteristics of the learning environment.

M. Aleksieva emphasizes the need for educational environments to evolve as flexible and technologically integrated systems capable of responding to the dynamic needs of learners and contemporary educational requirements (Aleksieva, 2024). Accordingly, intelligent school environments are increasingly oriented toward the use of data for adapting educational content, organizing learning activities, and improving interactions among participants in the educational process.

A significant component of a sustainable educational ecosystem is the capacity to provide dynamic feedback and monitor learner development across diverse educational situations. The integration of learning analytics and AI-based systems supports the creation of models for analyzing learning activity, participation, and cognitive engagement. George Siemens considers analytical mechanisms a means of optimizing educational processes and supporting the development of adaptive pedagogical decisions (Siemens & Long, 2011).

In primary education, the sustainability of the learning process is associated not only with the technological infrastructure of the environment but also with the ability to establish stable patterns of interaction, motivation, and social participation. Ir. Mishkova-Yotova emphasizes the importance of interactive and collaborative pedagogical practices for developing active learning environments and fostering communicative engagement among learners (Mishkova-Yotova, 2024).

In the work of M. Baltov, sustainable development is viewed as a process based on effective management, adaptability, and the intelligent use of resources within dynamic social and technological environments (Baltov, 2023). Applied to educational contexts, these principles support the development of school ecosystems in which technologies facilitate

the sustainable advancement of learning processes through continuous analysis, adaptation, and optimization of educational interactions.

From this perspective, the intelligent school ecosystem can be understood as an integrated environment in which digital twins, analytical technologies, and pedagogical practices operate in synergy to support the development of a sustainable, adaptive, and effective learning process in primary education.

2. Conceptual Model of an Intelligent and Sustainable Educational Ecosystem in Primary Education

The dynamics of digital transformation in education place increasing emphasis on the development of models that ensure effective interaction among technological innovations, pedagogical practices, and the social environment. Within the framework of Education 5.0, educational institutions are increasingly oriented toward the development of intelligent educational ecosystems capable of adapting the learning process to the individual characteristics of learners, supporting informed pedagogical decision-making, and creating conditions for the sustainable development of the educational environment.

The advancement of technologies based on artificial intelligence, learning analytics, and educational data processing expands the possibilities for monitoring and analyzing processes taking place within educational systems. In this context, the concept of the digital twin acquires particular significance, as it enables the creation of dynamic virtual representations of educational objects, processes, and participants that reflect their state, development, and interactions in real time. The application of this approach in education creates opportunities for a higher degree of personalization, adaptability, and effectiveness of the learning process.

The role of intelligent technologies is particularly important in primary education, where the foundations of literacy, mathematical culture, social skills, and learning motivation are established. The diversity of educational needs, individual rates of development, and the need for timely pedagogical support highlight the importance of models that provide continuous feedback and facilitate the adaptation of educational activities to the development of each child.

M. Aleksieva emphasizes that the contemporary educational environment requires the integration of digital technologies, adaptive learning models, and innovative pedagogical practices oriented toward the learner and their active participation in the learning process (Aleksieva, 2024). This understanding highlights the need to develop systems that integrate

the technological and pedagogical dimensions of education within a unified functional framework.

Based on the theoretical analysis and the scientific perspectives examined in this study, a conceptual model of an intelligent and sustainable educational ecosystem in primary education is proposed. The model views the learning process as a dynamic and interconnected system in which the learner occupies a central position, while digital technologies function as instruments for analyzing, adapting, and improving educational interactions. The conceptual framework is based on the interaction among digital twins, analytical technologies, pedagogical practices, socio-psychological factors, and mechanisms for the sustainable management of the educational environment.

In accordance with this logic, the model is structured around five interrelated components that function as elements of a unified intelligent educational ecosystem.

A distinctive feature of the proposed model is the integrated nature of the interactions among the technological, pedagogical, social, and organizational components of the educational environment. The model is grounded in the understanding that effective management of the learning process requires continuous interaction among educational data, pedagogical decisions, and learner characteristics. From this perspective, an intelligent educational ecosystem can be viewed as a dynamic system in which information about learner development is transformed into a resource for adapting and improving educational interactions.

If we accept that a digital twin, by its conceptual nature, represents a dynamic virtual model of a real object or process that reflects its state, characteristics, and development over time (Grieves, 2014; Tao et al., 2019), then in an educational context it can be interpreted as an intelligent model of the learner that integrates information about educational progress, cognitive activity, learning behavior, and competency development. Such an understanding extends the application of digital twins beyond their technological function and positions them as a tool for supporting pedagogical management, personalized learning, and the development of adaptive educational environments.

From this perspective, the digital twin serves as a connecting mechanism between the processes of observation, analysis, and pedagogical intervention. By integrating data on learner development, it creates conditions for establishing a continuous feedback system in which educational decisions are based on up-to-date information about the individual characteristics, needs, and potential of each learner. In this way, a conceptual framework is formed that combines the capabilities of intelligent technologies with the principles of personalized and sustainable education that characterize contemporary Education 5.0 models.

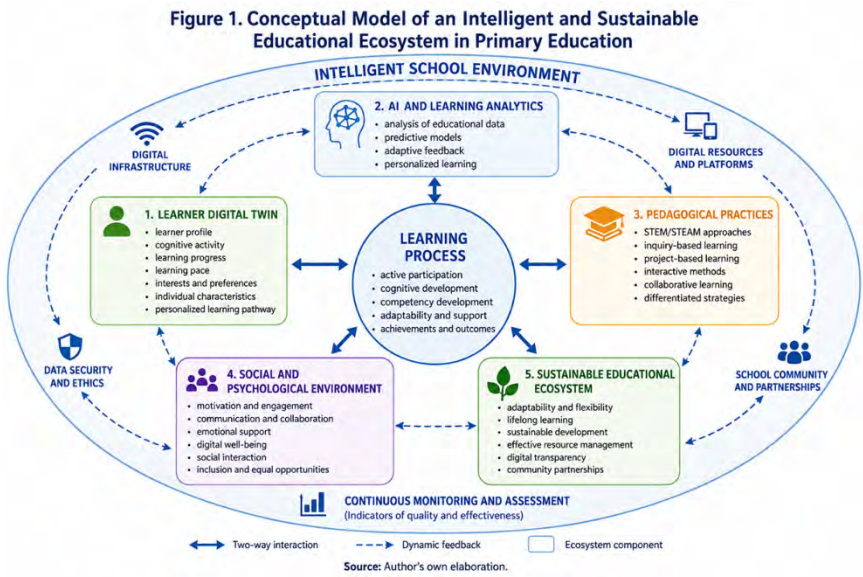


Figure 1. Conceptual Model of an Intelligent and Sustainable Educational Ecosystem in Primary Education

The first component of the model is the learner's digital twin, which serves as the central coordinating element within the intelligent educational ecosystem. It integrates information related to learning outcomes, learning activity, cognitive development, interests, and participation in various educational activities. Through the continuous updating of these data, a comprehensive picture of learner development is formed, enabling the monitoring of individual learning trajectories and supporting the provision of more precise educational support. Within the framework of the model, the digital twin provides the informational foundation upon which subsequent processes of analysis, interpretation, and pedagogical planning are built.

The second component comprises AI-based technologies and learning analytics, through which educational data are transformed into pedagogically meaningful information. According to George Siemens and Phil Long (2011), learning analytics supports the understanding and optimization of educational interactions through the systematic analysis of data. In the proposed model, the analytical layer functions as a connecting mechanism between educational data and pedagogical action. It enables the identification of developmental trends, the monitoring of changes in learning outcomes, and the creation of conditions for more informed planning of educational activities.

The third component encompasses pedagogical practices through which the results of data analysis are implemented within the educational environment. It includes STEM/STEAM activities, project-based learning, gamification, collaborative learning, and interdisciplinary educational approaches. Irina Mishkova-Yotova emphasizes the importance of interactive methods for stimulating cognitive activity and promoting learners' active participation in the learning process (Mishkova-Yotova, 2024). Within the model, pedagogical practices serve as a mechanism through which analytical insights are transformed into concrete educational decisions aimed at the development of knowledge, skills, and competencies.

The fourth component includes the social and psychological environment as a significant factor influencing the effectiveness of the learning process. It encompasses motivation, communication, emotional engagement, a sense of belonging, and interactions among participants in the educational process. Zlatina Dimitrova views the educational ecosystem as a space in which technological, pedagogical, and social factors operate in conditions of mutual interdependence (Dimitrova, 2022). In primary education, this component contributes to the development of a positive educational climate that encourages active participation, self-confidence, and a sustained interest in learning.

The fifth component is associated with the sustainable management of the educational environment. It integrates processes related to the efficient use of resources, technological integration, organizational adaptability, and the development of innovative educational practices. According to M. Baltov (2023), sustainable development is based on connectivity, efficiency, and the intelligent management of available resources. Within the proposed model, this component provides conditions for the long-term functioning and development of the educational ecosystem while supporting its continuous improvement in response to evolving educational needs.

A distinctive feature of the proposed model is the integrated nature of the interactions among its components. Each component performs specific functions while simultaneously operating as part of a unified system oriented toward learner development. The digital twin provides data on educational development, analytical technologies interpret these data, pedagogical practices implement educational decisions, the socio-psychological environment supports active learner participation, and sustainable management mechanisms ensure the effective functioning of the entire system. It is precisely this interconnectedness that transforms the model into an intelligent educational ecosystem capable of supporting continuous development, adaptability, and sustainability within the learning process.

2.1. Mechanism of Functioning of the Conceptual Model

The functioning of the proposed model is based on a continuous exchange of data, information, and pedagogical actions among the individual components of the intelligent educational ecosystem. At the core of this process lies the understanding that educational development is a dynamic phenomenon influenced by multiple interconnected factors—cognitive, social, emotional, and organizational. Therefore, the model does not view learning as a sequence of isolated activities but rather as a system of interacting processes in which every educational interaction generates information and creates conditions for the subsequent adaptation of the educational environment.

The mechanism of operation is implemented through a cyclical sequence of three interconnected stages: the generation of educational data, analytical processing, and pedagogical intervention. Each stage performs a specific function, yet the effectiveness of the model derives from their continuous interconnection. In this way, an adaptive mechanism is established through which the educational environment responds to changes in learner development and creates conditions for timely support and continuous improvement of the learning process.

The first stage is related to the generation and accumulation of educational data. Information is produced through learners' participation in various educational, research, and social activities and reflects multiple dimensions of their development. At this stage, the digital twin functions as an integration environment in which incoming data are organized and continuously updated to reflect the current state and dynamics of learner development.

The second stage involves the analytical processing and interpretation of information through learning analytics and AI-based technologies. The analytical module transforms accumulated data into indicators that support the understanding of educational processes and developmental trends among learners. As a result, a foundation is created for identifying areas in which further stimulation, enrichment, or adaptation of educational activities may be beneficial. In this way, data acquire pedagogical value and become a resource for informed educational decision-making.

The practical application of this mechanism can be illustrated through the development of reading literacy in primary education. During activities involving literary and informational texts, the digital twin collects information related to reading fluency, reading accuracy, text comprehension, information retrieval, and the ability to formulate conclusions. If the data indicate a high level of reading technique combined with a need for further

development of interpretative skills, the teacher may design activities focused on content analysis, discussion of characters and events, identification of cause-and-effect relationships, and the justification of personal viewpoints. In this way, the digital twin supports the development of functional literacy through the targeted adaptation of the learning process.

A similar mechanism can be applied in mathematics education. During the acquisition of numerical concepts and arithmetic operations, the digital twin records performance on different types of tasks, completion time, problem-solving strategies, and the degree of learner independence. If it is observed that a learner successfully solves tasks supported by visual representations while requiring additional practice with abstract numerical operations, the teacher may introduce more visual models, practical situations, and progressively challenging tasks. Such an approach contributes to the development of mathematical literacy, logical reasoning, and confidence in problem-solving.

The functioning of the model becomes particularly valuable within STEM learning environments. During the implementation of inquiry-based projects, the digital twin monitors learner participation throughout all stages of the activity, including question formulation, research planning, data collection, analysis of results, and presentation of solutions. For example, in a project related to waste separation at school, the system may record learners' engagement in gathering and processing information, their ability to collaborate in teams, and their skills in presenting evidence-based conclusions. The resulting data support the assessment of inquiry skills, critical thinking, and competencies related to sustainable development.

The third stage of the model is associated with pedagogical decision-making and the adaptation of educational activities. Based on the results of the analysis, teachers select appropriate methods, resources, and forms of instruction aligned with learner development. In this respect, the digital twin functions as an intermediary between educational data and pedagogical practice, supporting the design of personalized learning scenarios and creating conditions for active participation in the learning process.

Following the implementation of educational activities, new data are generated and incorporated into the learner's digital profile. Thus, the model operates as a continuous feedback system in which each new interaction contributes to a more accurate understanding of learner development and to the ongoing refinement of pedagogical decisions.

The cyclical nature of the model creates conditions for the sustainable development of the educational ecosystem. Data support not only individualized educational assistance but also decision-making at the classroom,

school, and educational community levels. In this sense, the digital twin becomes a connecting element linking the learner, the teacher, the educational environment, and the strategic management of educational processes.

The mechanism of the model can therefore be represented as a closed cycle of continuous improvement of the learning process. Data generated by learners are transformed into pedagogically meaningful information through analytical technologies, supporting the planning of educational activities. Implemented pedagogical decisions create new educational interactions and generate new data that update the digital twin. In this way, the model ensures a continuous connection among observation, analysis, pedagogical decision-making, and educational development, making adaptability and sustainability fundamental characteristics of the intelligent educational ecosystem.

2.2. Expected Pedagogical Effects of the Model

The proposed conceptual model outlines opportunities for enhancing the learning process in primary education through the integration of educational data, intelligent technologies, and contemporary pedagogical practices. The expected pedagogical effects can be examined at several interconnected levels—the learner, the teacher, the educational environment, and the educational ecosystem. This multidimensional impact derives from the systemic nature of the model, in which the interaction between the digital twin, analytical technologies, and pedagogical practices creates conditions for the continuous improvement of the learning process.

At the learner level, one of the most significant effects is related to the personalization of education. Through the systematic monitoring of educational progress, cognitive activity, preferred learning strategies, and individual developmental pace, opportunities are created to adapt educational activities to the needs of each child. This supports the implementation of a differentiated approach in which learners receive appropriate support and opportunities for development in accordance with their interests, abilities, and educational potential.

Another important effect concerns the development of reading literacy. Data generated through the digital twin make it possible to monitor text comprehension, information retrieval and interpretation, the formulation of conclusions, and the ability to express opinions in a reasoned manner. This supports the planning of educational activities aimed at developing functional literacy, critical thinking, and the ability to work with diverse information sources from the earliest years of schooling.

With regard to mathematical literacy, the model creates conditions for more precise monitoring of the acquisition of mathematical concepts, algorithms, and problem-solving strategies. Information concerning educational progress supports the selection of activities aimed at developing logical reasoning, analytical skills, and the ability to apply mathematical knowledge in practical contexts. In this way, the model contributes to the formation of a sustainable mathematical culture and increased confidence in solving problems.

A particularly significant effect is expected in relation to the development of STEM competencies and inquiry-based skills. The integration of digital twins into project-based and research-oriented activities provides opportunities to monitor processes such as observation, experimentation, data analysis, teamwork, and the presentation of results. This supports the development of problem-solving abilities, decision-making skills, and the application of knowledge in real-life situations. The development of such competencies corresponds to the views of Aleksieva, Kolarova, and Mishkova-Yotova (2024), who regard STE(A)M education as an environment that fosters creativity, inquiry-based thinking, and active learner participation.

In addition to cognitive development, the model also supports the formation of social and communication competencies. By monitoring participation in collaborative activities, cooperation, and interactions among learners, conditions are created for a deeper understanding of social dynamics within the educational environment. This contributes to the development of a supportive and inclusive school community based on active participation, collaboration, and mutual respect.

At the teacher level, the model provides opportunities for more informed pedagogical management. The digital twin offers structured information regarding learner development, supporting curriculum planning, the selection of teaching methods, the organization of differentiated educational activities, and the monitoring of educational outcomes. As a result, teachers have access to a broader evidence base for pedagogical decision-making and for supporting the individual potential of each learner.

The interaction between school and family is particularly important in primary education. Information generated through the digital twin provides clearer visualization of educational progress and facilitates more effective communication between teachers and parents. This creates conditions for building sustainable partnerships aimed at supporting learners' educational development and overall well-being.

At the level of the educational environment, the model supports decision-making based on authentic educational data. The analysis of information related to learner progress and participation contributes to the optimization of educational activities, the more efficient use of resources, and the development of an adaptive school environment oriented toward sustainable development.

Furthermore, the model creates opportunities for improving educational quality through evidence-based management. The continuous collection and interpretation of educational data support the identification of emerging needs, the evaluation of pedagogical interventions, and the refinement of educational practices. Such a data-informed approach contributes to the establishment of a culture of continuous improvement, where educational decisions are grounded in objective information about learner development and educational effectiveness.

The model also contributes to strengthening the adaptive capacity of the educational ecosystem. Through the interaction between technological tools, pedagogical approaches, and social factors, the system becomes capable of responding flexibly to changing educational needs and contextual challenges. This adaptability enhances the resilience of the educational environment and supports its long-term sustainability.

In a broader context, the proposed model supports the development of an intelligent and sustainable educational ecosystem in which technological solutions, pedagogical practices, and social interactions function as interconnected elements of a unified system. The conceptual model integrates the technological, pedagogical, and social dimensions of the educational environment into a framework for the intelligent management of the learning process. Through the interaction between the learner's digital twin, analytical technologies, pedagogical practices, and mechanisms for sustainable development, conditions are created for the establishment of an adaptive, personalized, and inclusive educational ecosystem in primary education.

3. Methodology of the Empirical Study

The development of a conceptual model requires empirical validation in order to examine its applicability within authentic educational settings. In the context of digital transformation and the increasing integration of intelligent technologies into education, it is important to explore how educational stakeholders perceive the potential of digital twins to support adaptive learning, pedagogical decision-making, and the sustainable development of educational environments. Consequently, the empirical

component of the study is designed to provide evidence regarding the relevance and practical applicability of the proposed model in primary education.

The methodological framework seeks to establish a connection between the theoretical foundations of the study and their potential implementation in educational practice. Through the collection and analysis of empirical data, the study aims to identify trends, perceptions, and expectations related to the use of digital twins as part of an intelligent and sustainable educational ecosystem.

3.1. Organization of the Study

The empirical study is aimed at examining attitudes toward the application of digital twins in an intelligent school environment and exploring their significance for the sustainable development of the learning process in primary education. The study is grounded in the understanding that the integration of intelligent technologies into education supports the development of adaptive pedagogical models oriented toward learners' individual characteristics and active participation in the educational process.

The methodological design of the study combines a quantitative approach with analytical interpretation of the obtained results. The primary method for collecting empirical data is a questionnaire survey, which provides opportunities to investigate pedagogical, technological, and psychological aspects related to the application of digital twins in the school environment.

The study was conducted among educational professionals and learners engaged in the use of digital technologies within the learning process. The selection of participants was focused on educational settings characterized by the implementation of innovative pedagogical practices, interactive teaching methods, and digital educational resources.

The questionnaire instrument was structured around several thematic dimensions:

- use of digital technologies in the learning process;
- attitudes toward intelligent educational systems;
- opportunities for personalized learning;
- adaptability of the educational environment;
- motivation and learner engagement;
- implementation of STEM/STEAM approaches;
- sustainable development of the school ecosystem.

The survey questions were designed to explore the relationship between intelligent technological solutions and the opportunities for optimizing the

learning process through the analysis, adaptation, and personalization of educational interactions. Particular attention was given to participants' perceptions of the potential of digital twins to support educational decision-making, improve learning experiences, and contribute to the development of adaptive educational environments.

Data processing involved the application of descriptive statistical methods, including frequency analysis, percentage distributions, and comparative interpretation of the results. This analytical approach enabled the identification of trends associated with the integration of digital twins into the school environment and their perceived impact on the adaptability and sustainability of the learning process.

The methodological framework of the study provides conditions for the practical validation of the proposed conceptual model of an intelligent and sustainable educational ecosystem in primary education. Furthermore, it offers an empirical basis for examining the potential contribution of digital twins to the development of data-informed pedagogical practices, personalized learning environments, and sustainable educational innovation.

3.2. Sample Characteristics and Research Instrument

The empirical study involved 62 students enrolled in the Master's degree programme *Preschool and Primary School Pedagogy* at Burgas Free University. The participants were purposefully selected due to their direct engagement in professional preparation for careers in preschool and primary education, as well as their active involvement in processes related to the digital transformation of educational environments. Their academic background and practical experience provide a valuable perspective on the implementation of intelligent technologies in contemporary educational practice.

The participants possess diverse educational and professional experiences, creating opportunities for a broader examination of attitudes toward the use of intelligent educational technologies, adaptive learning environments, and the development of sustainable educational ecosystems. Their profile is particularly relevant to the objectives of the study, as they represent future educational professionals who are expected to integrate innovative digital solutions into teaching and learning processes.

To achieve the objectives of the study, an original questionnaire instrument was developed and structured into thematic blocks corresponding to the components of the proposed conceptual model of an intelligent and sustainable educational ecosystem.

The first thematic block focused on the extent to which digital technologies and interactive educational resources are used in educational practice. The questions in this section explored the frequency of using digital platforms, STEM/STEAM activities, and technologies that support educational interaction and learner engagement.

The second thematic block examined attitudes toward intelligent educational systems and the possibilities for adapting learning to individual learner characteristics. Particular emphasis was placed on personalized learning, adaptive feedback, and the use of analytical mechanisms for monitoring educational progress.

The third thematic block addressed the pedagogical and psychological dimensions of the digital learning environment, including motivation, engagement, communication, and active participation in educational activities. This section explored the perceived contribution of interactive technologies to the development of cognitive activity and sustained interest in learning.

The fourth thematic block focused on the sustainable development of the school ecosystem through the use of intelligent technological solutions that promote adaptability, inclusion, and effective management of educational environments.

The questionnaire included closed-ended, semi-open, and scale-based questions, enabling quantitative analysis and comparative interpretation of the results. A five-point Likert scale was employed to measure levels of agreement, frequency of use, and attitudes toward the application of intelligent technologies in education.

The developed research instrument provides conditions for the systematic examination of relationships between the digital environment, adaptive learning processes, and the potential of intelligent technologies to support the development of a sustainable educational ecosystem. Furthermore, it enables the collection of empirical evidence relevant to the practical validation of the proposed conceptual model within the context of primary education.

4. Analysis of the Empirical Research Results

The analysis is aimed at examining attitudes toward the application of digital twins in educational environments and evaluating their potential contribution to the development of an intelligent and sustainable educational ecosystem in primary education.

The collected data indicate a high level of acceptance of intelligent technologies as a means of improving the teaching and learning process. The

mean values for all examined indicators exceed 4.40 on the five-point scale, demonstrating a clearly positive attitude toward the use of digital solutions in contemporary educational practice.

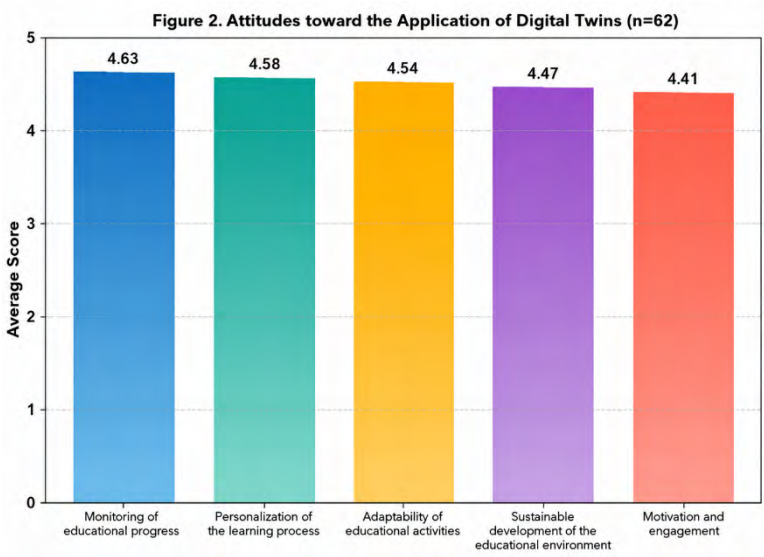


Figure 2. Attitudes toward the Application of Digital Twins in the Learning Process (n = 62)

The highest mean value was recorded for the indicator *"Monitoring of Educational Progress"* (M = 4.63), followed by *"Personalization of the Learning Process"* (M = 4.58) and *"Adaptability of Educational Activities"* (M = 4.54). These findings reveal a clear preference for functionalities related to monitoring, analyzing, and interpreting learners' educational progress.

This tendency may be interpreted as a reflection of the growing role of data in the educational process. Future educational professionals perceive digital twins primarily as a tool for supporting pedagogical decision-making based on information about learners' development, activity, and educational achievements. Such an interpretation corresponds to the understanding of Michael Grieves (2014), who defines the digital twin as a dynamic model of a real object or process that enables continuous analysis and updating of information.

From a pedagogical perspective, the high ratings for monitoring, personalization, and adaptability indicate an orientation toward educational models based on learners' individual characteristics and needs. The results support M. Aleksieva's view that digital transformation creates conditions

for the development of personalized educational models aimed at active participation and individualized educational support (Aleksieva, 2024).

Particular interest is associated with the minimal difference between the indicators *"Personalization of the Learning Process"* and *"Adaptability of Educational Activities"* (0.04 points). This suggests that the participants perceive these two aspects as complementary elements of a contemporary educational environment. Personalization is associated with the individual characteristics of the learner, whereas adaptability is viewed as the capacity of the educational system to respond to those characteristics through appropriate pedagogical decisions.

The results also demonstrate a relatively balanced distribution of ratings across all indicators, with a difference of only 0.22 points between the highest and the lowest mean values. This finding indicates a generally positive perception of digital twins and an understanding of them as a comprehensive technological solution that integrates multiple dimensions of the educational process. Rather than being viewed solely as a tool for monitoring outcomes, digital twins are perceived as a mechanism that supports both individualized learning and the development of adaptive educational environments.

Particular attention should also be paid to the indicators *"Sustainable Educational Environment"* (M = 4.47) and *"Motivation and Engagement"* (M = 4.41). Although these values are slightly lower than those of the other indicators, they remain within the range of very high evaluations. This may suggest that respondents perceive the contribution of digital twins to motivational and social aspects of learning as indirect, achieved primarily through the creation of more adaptive educational conditions rather than through direct influence on learners' attitudes and behavior.

From the perspective of the proposed conceptual model, the findings confirm the significance of the interaction among its core components. The high evaluations of educational progress monitoring and personalized learning support the role of the digital twin and analytical technologies as a foundation for pedagogical decision-making. At the same time, the positive attitudes toward adaptability and sustainability indicate an awareness that technological solutions should be integrated into a broader educational ecosystem that includes pedagogical practices, social interactions, and mechanisms for the long-term development of the school environment.

Overall, the results demonstrate a readiness to adopt intelligent educational technologies and support the assumption that digital twins have the potential to become a key component of future adaptive and sustainable educational ecosystems. This aligns with contemporary trends associated

with Education 5.0, where data, analytical mechanisms, and pedagogical practices function as interconnected components of a unified system for managing and continuously improving the learning process.

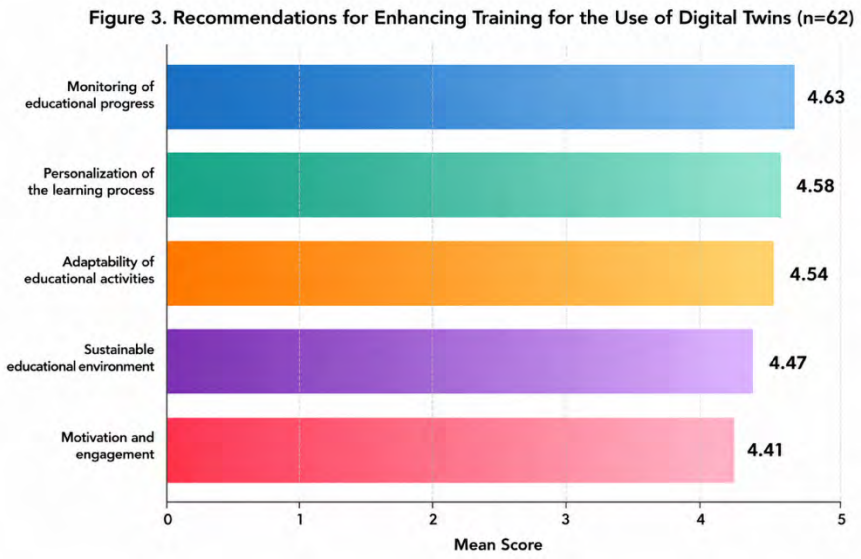


Figure 3. Ranking of the Main Dimensions of the Intelligent Educational Ecosystem (n = 62)

The ranking of the indicators reveals a relatively balanced distribution of the evaluations. The difference between the highest and the lowest mean value is only 0.22 points, indicating a high degree of consistency in participants' perceptions. This finding suggests that digital twins are not viewed merely as an isolated technological innovation but rather as an integral component of a broader system of interconnected educational practices and processes.

The indicator *"Sustainable Educational Environment"* achieved a mean score of **M = 4.47**. Although this value is slightly lower than those of the other indicators, it remains within the range of strong positive evaluations. The results indicate an awareness of the relationship between technological innovation and the sustainable development of educational environments. Participants perceive intelligent technologies as a means of increasing the efficiency, adaptability, and long-term sustainability of educational processes.

This attitude corresponds to Baltov's conceptualization of sustainable development as a process based on intelligent management of resources, processes, and organizational environments (Baltov, 2023). Within an

educational context, such an approach implies the development of an ecosystem in which technological connectivity, pedagogical effectiveness, and sustainability function as complementary and mutually reinforcing dimensions.

The relatively high evaluation of sustainability is particularly significant because it demonstrates that respondents recognize the broader systemic impact of digital technologies beyond their immediate instructional functions. Digital twins are perceived not only as tools for monitoring and personalizing learning but also as mechanisms capable of supporting evidence-based educational management and continuous improvement of educational practices. This perception aligns with contemporary approaches to Education 5.0, which emphasize the integration of intelligent technologies with human-centered and sustainable educational development.

Furthermore, the close clustering of all indicator values suggests that participants perceive the dimensions of the proposed model as strongly interconnected. Monitoring educational progress, personalizing learning, adapting educational activities, promoting learner engagement, and supporting sustainability are viewed as complementary elements of a single educational ecosystem rather than as independent technological functions. Such a perspective reinforces the theoretical assumption underlying the proposed conceptual model that the effectiveness of intelligent educational environments depends on the interaction among technological, pedagogical, social, and organizational components.

From this perspective, the findings provide empirical support for the proposed conceptual framework. They suggest that future educational professionals recognize the potential of digital twins to function as a connecting mechanism between educational data, pedagogical decision-making, learner development, and sustainable educational management. Consequently, digital twins may be regarded as an important enabling technology for the development of adaptive, learner-centered, and sustainable educational ecosystems in primary education.

The analysis of deviations from the neutral scale value (3.00) provides additional insight into the strength and intensity of participants' attitudes toward the application of digital twins in educational settings. While the mean values presented in the previous figures indicate the direction of respondents' perceptions, the deviation analysis allows for a more precise assessment of the extent to which these perceptions differ from a neutral position.

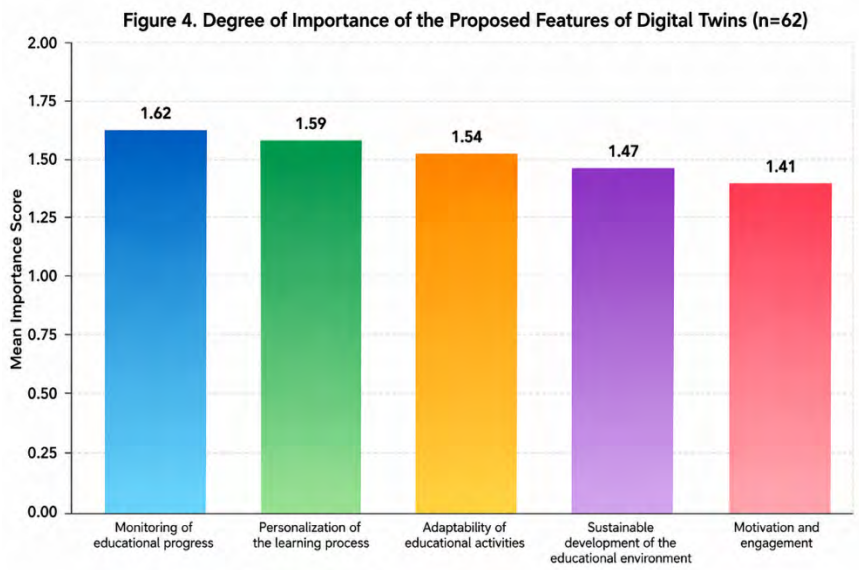


Figure 4. Deviation of Mean Scores from the Neutral Value (n = 62)

The largest deviation was observed for the indicator *"Monitoring of Educational Progress"* (**+1.63**), followed by *"Personalization of the Learning Process"* (**+1.58**) and *"Adaptability of Educational Activities"* (**+1.54**). These values indicate a strong consensus among respondents regarding the educational benefits associated with digital twins. The results suggest that participants primarily associate the potential of digital twin technology with the ability to collect, analyze, and utilize educational data in support of informed pedagogical decision-making.

The relatively small differences between these three indicators further emphasize the interconnected nature of monitoring, personalization, and adaptability within contemporary educational environments. Respondents appear to perceive these dimensions as complementary components of a single pedagogical process in which data-driven insights enable the continuous adjustment of educational activities to learners' individual characteristics and needs.

A somewhat lower, yet still substantial, deviation was recorded for the indicator *"Motivation and Engagement"* (**+1.41**). This finding suggests that participants recognize motivation and engagement as outcomes influenced by multiple factors beyond technology alone. In this respect, intelligent technological solutions are viewed as supportive mechanisms whose effectiveness depends on their integration with appropriate pedagogical approaches, social interactions, and meaningful learning experiences. Such

an interpretation reinforces the idea that technology itself does not automatically increase learner engagement but creates conditions that may facilitate higher levels of participation when combined with effective educational practices.

Similarly, the indicator *"Sustainable Educational Environment"* demonstrates a strong positive deviation from neutrality, indicating that respondents acknowledge the broader systemic contribution of digital technologies to educational development. The findings suggest an awareness that intelligent technologies can support not only individual learning processes but also the long-term improvement of educational environments through enhanced adaptability, evidence-based management, and more effective utilization of educational resources.

From a theoretical perspective, the observed deviations provide empirical support for the proposed conceptual model of an intelligent and sustainable educational ecosystem. The consistently high positive deviations across all indicators demonstrate that respondents perceive digital twins as a multidimensional educational tool rather than as a purely technological innovation. Their value is associated simultaneously with learner development, pedagogical effectiveness, adaptive educational management, and sustainable educational improvement.

The overall pattern of results confirms the main research hypothesis and supports the proposed conceptual framework. The findings indicate that future educational professionals perceive digital twins as a mechanism capable of facilitating educational progress monitoring, personalized learning, adaptive educational practices, and the sustainable development of the learning environment in primary education. Furthermore, the strong positive deviations from the neutral value suggest a high level of readiness for the integration of intelligent technologies into future educational practice, consistent with the principles of Education 5.0 and data-informed educational innovation.

5. Discussion

The findings of the study provide substantial grounds for considering digital twins as a promising mechanism for supporting the development of intelligent and sustainable educational ecosystems in primary education. The attitudes expressed by the students enrolled in the Master's programme in Preschool and Primary School Pedagogy reveal a clear awareness of the potential of intelligent technologies to enhance educational processes through data-informed decision-making, personalized learning pathways, and adaptive pedagogical interventions.

The results are consistent with contemporary trends in the digital transformation of education, which emphasize the increasing role of educational data, artificial intelligence, and learning analytics in supporting learner-centered educational environments. The high evaluations assigned to indicators related to educational progress monitoring, personalization, and adaptability suggest that future educational professionals perceive digital technologies not merely as supplementary instructional tools but as strategic resources capable of improving the effectiveness and responsiveness of educational systems.

Particularly noteworthy is the highest-rated indicator, *"Monitoring of Educational Progress."* This finding highlights a growing recognition of the importance of evidence-based educational practices and continuous feedback mechanisms. In contemporary educational theory, monitoring is increasingly viewed as a prerequisite for informed pedagogical intervention, allowing educators to identify learning patterns, diagnose educational needs, and provide timely support. From this perspective, the digital twin extends the capabilities of traditional learning analytics by creating a dynamic representation of learner development that evolves continuously through the accumulation and interpretation of educational data.

The strong support for *personalized learning* and *adaptive educational activities* further reinforces this interpretation. The relatively small differences among these indicators suggest that respondents perceive them as closely interconnected dimensions of the same educational process. Personalization requires a detailed understanding of individual learner characteristics, while adaptability reflects the educational system's capacity to respond effectively to these characteristics. Consequently, the digital twin may be viewed as a mediating mechanism that links learner data with pedagogical action, enabling a more flexible and responsive learning environment.

These findings support M. Aleksieva's view that contemporary educational transformation requires the integration of intelligent technologies capable of facilitating individualized educational experiences and enhancing learner participation (Aleksieva, 2024). Within this framework, the digital twin can be interpreted as an advanced educational profile that supports not only the observation of learner performance but also the design of differentiated instructional strategies aligned with learners' developmental trajectories.

An additional contribution of the findings lies in the perception of digital twins as components of a broader educational ecosystem rather than isolated technological innovations. Respondents appear to recognize that

the effectiveness of intelligent technologies depends on their integration within a network of pedagogical, organizational, and social relationships. This perspective corresponds to Dimitrova's understanding of the educational ecosystem as a dynamic environment in which technological infrastructure, pedagogical practices, institutional culture, and social interactions function in mutual interdependence (Dimitrova, 2023).

From an ecosystem perspective, the digital twin performs a coordinating function by facilitating the flow of information between different actors and processes within the educational environment. Such a role is particularly significant in primary education, where educational success depends on the interaction between learners, teachers, families, and the broader school community. Consequently, the value of digital twins extends beyond individual learner support and encompasses the optimization of educational interactions across the entire ecosystem.

The findings also provide important insights regarding the relationship between digital twins and sustainable educational development. Although the indicator *"Sustainable Educational Environment"* occupies the fourth position in the ranking, its mean score remains notably high. This result suggests that respondents associate intelligent technologies with long-term educational improvement rather than solely with short-term instructional efficiency. The ability to collect, interpret, and utilize educational data systematically may contribute to more effective resource allocation, improved organizational adaptability, and evidence-based educational management.

Such an interpretation is consistent with Baltov's conceptualization of sustainability as a process grounded in intelligent resource management, adaptability, and continuous improvement within complex organizational environments (Baltov, 2023). In educational settings, sustainability increasingly depends on the capacity of institutions to transform data into knowledge and knowledge into informed action. Viewed from this perspective, digital twins can contribute to sustainable educational development by supporting continuous monitoring, strategic planning, and adaptive management processes.

The relatively lower—though still strongly positive—evaluation of *"Motivation and Engagement"* offers an additional analytical perspective. The result suggests that participants perceive learner motivation as a multidimensional construct shaped by technological, pedagogical, psychological, and social factors. While intelligent technologies can facilitate engagement through personalization and interactive learning experiences, motivation ultimately emerges through meaningful educational interactions and supportive learning environments.

This interpretation aligns with Mishkova-Yotova's position that technological innovation achieves its greatest educational impact when combined with appropriate pedagogical strategies, active learning methods, and learner-centered educational design (Mishkova-Yotova, 2021). Consequently, the findings indicate that respondents do not attribute educational success exclusively to technology but rather recognize the importance of balancing technological innovation with pedagogical expertise and human interaction.

From a broader theoretical perspective, the results suggest a shift from technology-centered to ecosystem-centered understandings of educational innovation. Rather than viewing digital twins merely as technological artifacts, participants appear to perceive them as instruments that facilitate communication between educational data, pedagogical practice, and institutional decision-making. This perspective is particularly relevant within the context of Education 5.0, where technology serves not as an end in itself but as a means of supporting human-centered, inclusive, and sustainable educational development.

The scientific contribution of the present study lies in the development of a conceptual model of an intelligent and sustainable educational ecosystem that integrates digital twins, learning analytics, pedagogical practices, socio-psychological factors, and sustainability principles within a unified analytical framework. The proposed model extends the application of digital twin technology beyond its traditional technological domain and positions it within the context of primary education, where personalization, adaptability, and early educational support play a critical role in learner development.

In summary, the findings indicate that future educational professionals perceive digital twins as a valuable resource for the development of contemporary educational environments characterized by data-informed decision-making, personalized learning, adaptive educational practices, and sustainable educational management. The results provide empirical support for the proposed conceptual model and highlight the need for future research focused on the practical implementation and validation of digital twins in authentic school settings. Further investigations may explore their impact on educational effectiveness, learner outcomes, teacher decision-making processes, and the long-term sustainability of intelligent educational ecosystems.

6. Conclusion

The present theoretical and empirical study explored the potential of digital twins as a transformative factor in educational ecosystems within the context of sustainable development and the Education 5.0 paradigm. The research focused on primary education, where the learning process is characterized by a high degree of developmental dynamics, the need for individualized support, and the creation of a learner-centered educational environment.

The theoretical analysis demonstrated that digital twins extend traditional approaches to educational management through the integration of data, analytical mechanisms, and intelligent technologies. In educational contexts, they create opportunities for developing adaptive learning models based on monitoring educational progress, personalizing learning activities, and supporting the individual development of learners.

The proposed conceptual model presents the intelligent and sustainable educational ecosystem as a system of interconnected components, including the learner's digital twin, learning analytics, pedagogical practices, the socio-psychological environment, and sustainable management of educational processes. The interaction among these components creates conditions for the development of an educational environment characterized by effectiveness, adaptability, and sustainability.

The results of the empirical study conducted among 62 students enrolled in the Master's programme *Preschool and Primary School Pedagogy* at Burgas Free University indicate a high level of support for the application of digital twins in educational practice. The highest evaluations were associated with opportunities for monitoring educational progress, personalizing the learning process, and adapting educational activities to the individual characteristics of learners. These findings reveal an understanding of intelligent technologies as instruments for improving educational processes and supporting the development of a sustainable educational environment.

The scientific contribution of the study lies in adapting the concept of digital twins to the specific characteristics of primary education and in developing a conceptual model that integrates technological, pedagogical, and organizational dimensions of an intelligent educational ecosystem. The proposed model extends existing research by emphasizing the interrelationship between personalized learning, analytical technologies, and the sustainable development of educational environments.

Future research directions include the practical implementation and validation of the proposed model in authentic school settings, the

development of educational digital twin prototypes, and the investigation of their impact on learning quality, educational outcomes, and the development of key competencies among learners. Particular attention should also be given to exploring the integration of artificial intelligence, adaptive learning systems, and learning analytics within intelligent educational ecosystems designed to support a sustainable educational future.

References:

1. Aleksieva, M. (2024). Digitalna transformatsiya i novi obrazovatelni standarti za universiteta na badeshteto.
2. Aleksieva, M. (2025). Guide on the Side – uchitelyat kato mediator na znanie, prezhivyavane i vdahnovenie v STEM epohata. Godishnik na Burgaskiya svoboden universitet, XLIII.
3. Aleksieva, M. (2025). Transformational Pedagogy and Preparation of Pedagogical Specialists for the Development of Entrepreneurial Competence in the Context of Education 5.0. Nauchna konferentsiya na Burgaskiya svoboden universitet.
4. Aleksieva, M., Kolarova, T., & Mishkova-Yotova, I. (2024). STE(A)M obrazovanie i staya na zagadkite v parvi klas chrez igrata „Prikazka ot zaklyuchen zamak“ za stimulirane na STEM umeniya i kreativnost. Savremenna humanitaristika, 20(1), 43–62.
5. Aleksieva, M., & Mishkova-Yotova, Ir. (2025). Interactive and Sustainable Education for the New Generation in the Digital World. Proceedings of the 11th International Scientific Conference Knowledge Based Sustainable Development, University of Barcelona, Spain.
6. Baltov, M. (2023). Circular Economy Impact over the Blue Growth and the Blue Careers. In Sustainable Development – Circular Economy, Critical Infrastructures, Green Transition. Proceedings of the XVIII IBS International Conference, Sofia.
7. Dimitrova, Zl. (2022). Mediyna gramotnost v nachalnoto uchilishte. Ruse: Gayana Buk End Art.
8. Mishkova-Yotova, Ir. (2024). Staya na zagadkite: integrirane na igrovi elementi v uchebnia protses. Savremenna humanitaristika.
9. Grieves, M. (2014). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. White Paper.
10. Schwab, K. (2016). The Fourth Industrial Revolution. Geneva: World Economic Forum.
11. Siemens, G., & Long, P. (2011). Penetrating the Fog: Analytics in Learning and Education. EDUCAUSE Review, 46(5), 30–40.
12. Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2019). Digital Twin Driven Smart Manufacturing. London: Academic Press.

IMPACT OF LIFE-LONG LEARNING ON QUALIFICATION MISMATCH

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Abstract: *In Europe, education-job mismatch has been continuously increasing during the last two decades. The share of employees with at least upper secondary education who work below their level of educational attainment, has increased more than 40% between 2000 and 2019. Lifelong learning could be a potential measure for reducing the extent of this mismatch by upgrading employees' knowledge, skills, and competencies. With regard to that, the current paper focuses on the link between continuing education of adults and overeducation. The study uses panel data on EU-27 (2020 onwards) over the period 2010-2019 for workers having completed upper secondary education (ISCED 3-4) or tertiary education (ISCED 5-8). The outcome implies that there is a negative link between the participation in continuing education and training and the degree of mismatch. This is more strongly expressed for upper secondary education and also for non-formal training. The empirical findings are in compliance with the explanations of the training investments given by the human capital theory.*

Keywords: *lifelong learning, continuing training, overeducation, qualification mismatch*

1. Introduction

In the current world of rapid changes, investments in continuing education and training play a crucial role for economic and social advance. They are expected to boost the company innovation capacity and successful new technology adoption, to reduce income differentiation and improve the quality of employment and working life [1,2]. European policy places an emphasis on participation in continuing education and training. The target regarding adult participation in education and training was updated to a rate of at least 47% over the 12-month period prior to the survey which should be reached by 2025 [3].

Continuing vocational education and training is an important tool for reducing the growing qualification mismatch across the European economies over the last two decades [4]. According to the definitions, a worker

is counted as part of vertical qualification mismatch if his or her years of schooling or educational degree completed differ from those required for one's job. In case of overeducation/overqualification, one's educational background exceeds the required one for his or her job. The average overqualification rate for the European Union was 22% is 2022 [5] reaching 36% in Spain, and 32% in Greece and Cyprus. A major reason for qualification mismatch, particularly overeducation accompanied by underskilling, digitalization, technology advance, and the recent AI invasion. Gussek et al. point out that today, well-educated people take jobs down the occupational ladder due to deficit of up-to-date knowledge and competencies. Therefore, continuing training is considered a powerful instrument for preventing skill obsolescence due to technology changes [6].

Therefore, this study focuses on the link between lifelong learning and continuing education and training, specifically, and qualification mismatch. It addresses the research void on this issue by checking the hypothesis that the higher rate of participation in continuing education and training is associated with a lower share of overeducated employees at a country level.

According to human capital theory, organisations are motivated to invest mainly in skill-specific training since this reduces the likelihood for the employee to switch the company after training thus leaving the current employer to bear the training costs [7]. Another reason for investing in specific skills is the replicability of workers. Those who have acquired skills useful for a particular company, are harder to be replaced. At the same time, general-skill training would be financed rather by the workers who are willing to accept a lower remuneration during the training period [8]. According to resource-based theory [9], the firm is considered a unique set of resources aiming at maximising its value. An enterprise could achieve efficiency gains by coordinating the efforts of different individuals who possess specific knowledge [10]. The continuous acquisition of knowledge is necessitated by the dynamic market conditions resulting from technological advance, changing consumer needs or competitive pressure. It is the primary task of the manager to coordinate this newly acquired knowledge.

2. Methodology and research output

To test the hypothesis that higher participation in lifelong learning decreases the degree of mismatch we use administrative data on the European economies. The sample includes the 26 EU member states (2020 onwards) over the period 2010-2021. Yearly data from Eurostat on participation rate

in education and training (4 weeks before the survey) as well as on the share of overeducated workers expressed as percentage of labor force with upper secondary or tertiary education completed. It is measured by the static approach assuming fixed mapping between one's educational degree acquired according to the International Standard Classification of Education (ISCED) and occupations based on the International Standard Classification of Occupations (ISCO) [11, p. 132]. In line with this approach, the jobs requiring tertiary education (ISCED 5-8) include managers, professionals, technicians and associated professionals. People performing all other jobs such as clerical support workers, craft and related trade workers, service and sales workers, etc., are counted as overeducated. Regarding upper secondary education, people with that educational degree performing elementary occupations are counted as overeducated.

The research hypothesis has been tested by employing the non-parametric Mann – Whitney U test. It is a standard non-parametric approach for testing the linkage between two variables [12]. It assumes that the samples come from populations with the same distribution [13]. Prior to test implementation we divided the whole population of 297 observations into three groups according to the intensity of lifelong learning. The following codes have been applied to the independent variable for each group (from 1 to 3):

- Group 1: the independent variable - rate of participation in education and training – equals 1, if the value is within the range (sample's minimum; sample's mean – 0.5*sample's standard deviation),
- Group 2: the independent variable equals 2, if the value is within the range (sample's mean – 0.5*sample's standard deviation; sample's mean + 0.5*sample's standard deviation), and
- Group 3: the independent variable - rate of participation in education and training – equals 3, if the value is above sample's mean + 0.5*sample's standard deviation and below sample's maximum value.

Group 1 indicates the least intensive participation in training; group 3 presents the most intensive participation while group 2 is at the margin. The Mann-Whitney test is performed for groups 1 and 3 and for groups 1 and 2. The dependent variable is the degree of overeducation for a given educational level – higher or upper secondary education.

Table 1. Outputs for the Mann-Whitney U test
a) Dependent variable: Overeducation for tertiary education graduates (ISCED 5-8)[*]

Participation by type of training and educational degree[**]	Group 1 vs. Group 3	Group 1 vs. Group 2
Formal and non-formal training	3347.00(1) (0.000)	5353.00 (0.971)
Formal training	3283.00(1) (0.001)	4714.00 (0.138)
Non-formal training	2746.00(1) (0.002)	5510.00(3) (0.062)

[*] See, the notes below table 1 for more on how it is measured.
[**]Independent (factor) variable. See, the notes table 1 for more on how it is measured.
(1), (2), (3) Significant at 0.01, 0.05 and 0.10 levels, respectively. P-values presented in brackets.

b) Dependent variable: Overeducation for upper secondary education graduates (ISCED 3-4)[*]

Participation by type of training and educational degree[**]	Group 1 vs. Group 3	Group 1 vs. Group 2
Formal and non-formal training	3410.00(1) (0.000)	4346.50 (0.104)
Formal training	3208.00(1) (0.007)	5219.50 (0.124)
Non-formal training	2276.00(1) (0.000)	4468.50(1) (0.001)

[*] See, the notes below table 1 for more on how it is measured.
[**] Independent (factor) variable. See, table 1 for more on how it is measured.
(1), (2), (3) Significant at 0.01, 0.05 and 0.10 levels, respectively. P-values presented in brackets.

The null hypothesis is that the two populations come from the same distribution. The results are presented in table 1. A level of significance less than 0.05 indicates that there is a statistically significant difference between the two populations at the 5% level. Both outputs shed more light on the impact not just of the involvement in continuing training but of the intensity of that involvement. It appears that for both education levels, the periods with the most active investments in continuing training (above the EU average + ½ st. dev.) and those with weak participation in lifelong learning (below the EU average - ½ st. dev.) lead to clearly expressed statistically significant differences in the pattern of overeducation. Non- significant differences (at the 5% level) have been observed between group 1 and group 2. Thus, the results imply that not only the participation in continuing education and training per se, but the degree of country's involvement in it matters for the labor market outcomes.

3. Conclusion

Along with the rising average educational attainment of the labor force, the increasing education-job mismatch, specifically overeducation, becomes a main concern posing serious challenges in both the educational systems and the labor market of the contemporary economies. Therefore, more studies are necessary for a robust empirical estimation of the impact of education on overeducation. The aim of the current paper is to address this research gap by focusing on the role of adult education and training.

Two main conclusions emerge. First, more intensive participation in continuing education and training is associated with a lower share of mismatched workers. This result is more strongly expressed for people with upper secondary education than those with higher education which follows the human capita theory. It explains the incidence of training by purely economic reasons such as higher productivity, wage, profits, employment and retention. According to several studies, the overeducated employees have relatively lower productivity than their just-educated peers [14] or comparatively lower wage premium [15]. Considering these findings, employers have an incentive to train overeducated to reduce their skill mismatch and improve their performance. The current research output supports those studies. On the other hand, workers themselves might be motivated to participate, or even finance the training, if they expect an increase in remunerations.

The second conclusion is that involvement in different forms of non-formal training, such as seminars, workshops, training courses, etc., matters more than participation in formal education and training. Non-formal education and training is usually provided by less formal institutions – establishments, organizations, or groups. The acquisition of knowledge and skills happens very consciously, while achieving a specific learning goal. Given that its various forms include on-the-job training, vocational programs as well as mentoring undertaken in the workplace, it is expected to supply practical work-related skills. On the other hand, formal training is offered by educational institutions and often leads to a certain educational degree or recognized diploma or certificate. It aims rather at improving the theoretical knowledge and the general professional background of the trainees. It is pointed out [28] that the overeducated workers experience higher turnover rates. In this regard, the companies are likely to invest in those employees by sponsoring the work-related training to improve the retention rate. This again complies with the prediction of the theory of human capital that companies would rather invest in skill-specific training. In case of such training, the likelihood of a worker staying employed at the

same company for a longer time increases thus reducing the rate of turnover.

The study has some practical some implications for the policymakers, specifically for countries with lower participation rates, by confirming the positive impact of continuing education and training on labor market sustainability. In light of the empirical evidence given above, it seems to be a powerful instrument for solving the issue of qualification mismatch observed in today's developed world.

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References:

1. C. Diebolt, R. Hippe, 2019. The long-run impact of human capital on innovation and economic development in the regions of Europe. Applied Economics, vol. 51, 541-563.
2. D. Krueger, K. B. Kumar, 2004. Skill-specific rather than general education: a reason for US-Europe growth differences?. Journal of Economic Growth, vol. 9, 167-207.
3. European Commission, 2021. Adult education and training in Europe: building inclusive pathways to skills and qualifications. Eurydice Report, Luxembourg.
4. Cedefop, 2012. The skill mismatch challenge in Europe. European Commission (ed.). Employment and social developments in Europe. Luxembourg: Publications Office, 351-394.
5. Eurostat, 2022. EU's employment rate peaks at 75% in 2022.
6. L. Gussek, L. Schned, Wiesche, 2021. Obsolescence in IT work: causes, consequences and counter-measures. Lecture Notes in Information Systems and Organisation, vol. 48, 572-586.
7. J. Mohrenweiser, T. Zwick, U. Backes-Gellner, 2019. Poaching and firm-sponsored training. British Journal of Industrial Relations, 57, 143–181.
8. K.–J. Fleischhauer, 2007. A Review of Human Capital Theory: Microeconomics. University of St. Gallen Department of Economics working paper series 2007 2007-01, Department of Economics, University of St. Gallen.
9. J. Barney, 1991. Firm resources and sustained competitive advantage. Journal of Management, vol. 17, 99-120.
10. R. Grant, 1996. Towards a knowledge-based view of the firm. Strategic Management Journal, vol. 17, 109-122.
11. Eurostat, 2009. The Bologna Process in Higher Education in Europe. Key Indicators on the Social Dimension and Mobility. Luxembourg: Office for Official Publications of the European Communities.

12. M. De Smith, 2015. Statistical Analysis Handbook. The Winchelsea Press, Drumlin Publications, UK.
13. J. McDonald, 2014. Handbook of Biological Statistics. 3rd Ed., Sparky House Publishing, Baltimore, US, 157-164.
14. R. Rumberger, 1987. The Impact of Surplus Schooling on Productivity and Earnings. The Journal of Human Resources, vol. 22, 24–50.
15. V. Jacobs, F. Rycx, M. Volral, 2022. Does Over-Education Raise Productivity and Wages Equally? The Moderating Role of Workers' Origin and Immigrants' Background. Discussion Paper Series No. 15074, IZA—Institute of Labor Economics.

THE DIGITAL TWINS CONCEPT AS A DRIVING FORCE FOR TECHNOLOGICAL TRANSFORMATION - PART I

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Abstract: *The Digital Twin (DT) concept has evolved into a significant paradigm for technological transformation; however, substantial diversity remains in its scholarly conceptualization and definition. This study examines selected scholarly conceptualizations of Digital Twins within five national research contexts: The United States, China, Bulgaria, Malaysia, and Indonesia. The objective is to identify and comparatively analyze the principal conceptual contributions, their originality, structural and functional characteristics, as well as their potential contribution to the development of Digital Twins as an instrument of technological transformation. A systematic comparative methodology is applied, combining bibliographic and bibliometric analysis with qualitative content analysis. Scientific publications constitute the primary unit of analysis, while particular attention is given to distinguishing established DT characteristics from specific authorial conceptual contributions. The analysis traces the conceptual evolution of Digital Twins and identifies increasing integration of physical and digital entities, data connectivity, synchronization, analytical capabilities, feedback mechanisms, and lifecycle functionality. Based on comparative analysis, the study proposes a generalized conceptualization of a Digital Twin as a dynamic digital representation of a physical object, process or system that uses data from the physical environment for monitoring, analysis, prediction, simulation and decision making support throughout its lifecycle. The study further emphasizes that the value of Digital Twins should be assessed not only through technological capabilities but also through measurable lifecycle value relative to their implementation and operational resources. The findings provide a conceptual basis for further research into Digital Twins as a driver of technological transformation.*

Keywords: *digital twin, technological transformation, digital transformation, conceptualization, bibliometric analysis, qualitative content analysis, lifecycle management*

I. INTRODUCTION

Digital transformation represents a complex and multidimensional process in which technological innovations interact with organizational, economic, institutional, and societal factors. Within this broader transformation, emerging digital technologies increasingly facilitate the integration of physical and virtual environments, the generation and analysis of real-time data, and the development of more advanced mechanisms for prediction, optimization, and decision-making. In this context, **Digital Twins** have emerged as an important technological and conceptual development, particularly in relation to Industry 4.0, smart manufacturing, cyber-physical systems, and data-driven decision making (Qi & Tao, 2018; Tao et al., 2019a; Fuller et al., 2020).

The concept of the Digital Twin has evolved considerably since its initial formulation. Grieves and Vickers (2017) conceptualized the Digital Twin in terms of the relationship between a physical entity, its virtual representation, and the data and information connecting the two. This conceptual foundation established the basis for subsequent interpretations of Digital Twins as dynamic representations capable of supporting the analysis and management of physical systems. Subsequent research has progressively expanded this understanding by incorporating real-time data exchange, modelling, simulation, monitoring, prediction, and optimization (Kritzinger et al., 2018; Tao et al., 2019a; Rasheed et al., 2020).

The development of the concept has also resulted in considerable diversity in the terminology and definitions employed in academic literature. Kritzinger et al. (2018) proposed a categorical distinction between a Digital Model, a Digital Shadow, and a Digital Twin, based primarily on the nature and direction of information exchange between the physical and digital domains. Similarly, Barricelli et al. (2019) demonstrated that the Digital Twin literature encompasses a range of definitions, characteristics, applications, and design implications, indicating that the concept cannot be reduced to a single universally accepted formulation. Jones et al. (2020), through a systematic literature review, further highlighted the heterogeneity of Digital Twin definitions and characteristics across the scholarly literature. These observations are particularly significant for the present study because they demonstrate that the Digital Twin should be understood as an **evolving scientific concept**, rather than as a concept with a single, universally established theoretical formulation.

The technological dimension of Digital Twins has developed in parallel with this conceptual evolution. Fuller et al. (2020) identify a range of enabling technologies underlying Digital Twin systems, including the Internet

of Things, cloud computing, data analytics, artificial intelligence, and simulation technologies. From this perspective, the Digital Twin represents not an isolated technological solution but an integration of multiple technologies that enables continuous interaction between physical systems and their digital counterparts. This integrative character contributes to the capacity of Digital Twins to support monitoring, prediction, optimization, and decision-making within increasingly complex technological environments (Fuller et al., 2020; Rasheed et al., 2020).

The relationship between Digital Twins and technological transformation has been particularly prominent in the context of Industry 4.0 and smart manufacturing. Qi and Tao (2018) positioned Digital Twins within a broader technological ecosystem involving big data, cyber-physical systems, and smart manufacturing. Tao et al. (2019a) further examined Digital Twins in relation to industrial applications and identified their potential to integrate physical systems, data, modelling, and intelligent analytical capabilities. In addition, Tao et al. (2019) examined the relationship between Digital Twins and cyber-physical systems in the context of smart manufacturing and Industry 4.0. These contributions indicate that the significance of Digital Twins extends beyond the digital representation of physical entities towards the transformation of production, operational, and managerial processes.

The expanding application domain of Digital Twins further illustrates the development of the concept. Although initially associated strongly with industrial and manufacturing systems, Digital Twins have subsequently been considered in relation to complex infrastructures, urban environments, and smart cities (Batty, 2018; Dembski et al., 2020). This expansion indicates that the conceptual boundaries of Digital Twins continue to develop as researchers apply the concept to increasingly complex physical, organizational, and socio-technical systems.

Despite the substantial growth of the Digital Twin literature, an important research gap remains. Existing studies have made significant contributions to the definition, classification, technological architecture, enabling technologies, and application domains of Digital Twins (Barricelli et al., 2019; Fuller et al., 2020; Jones et al., 2020). However, comparatively limited attention has been devoted to systematically identifying and comparing the **distinctive conceptual contributions advanced by individual authors within different national research contexts**. In particular, there remains a need for an analytical framework capable of distinguishing established characteristics of Digital Twins from author-specific conceptual

innovations and of assessing the significance of these contributions for technological transformation.

This distinction is fundamental to the present research. The objective is not simply to establish how Digital Twins are defined or applied in different countries, but to determine **what individual authors contribute to the conceptual development of Digital Twins**. An authorial conceptualization is therefore understood in this study as a structured scholarly proposition encompassing specific definitions, characteristics, structural elements, functional relationships, interaction mechanisms, and anticipated outcomes associated with Digital Twins. The analytical focus consequently shifts from the technology itself towards the **contribution embodied in the respective conceptualization**.

The selection of the **United States, China, Bulgaria, Malaysia and Indonesia** provides an appropriate comparative setting for such an investigation. These countries represent different technological, economic, institutional, and research environments, within which scholars have developed and articulated different perspectives on emerging digital technologies. The national dimension is therefore not treated merely as a geographical classification but as a contextual variable within which particular scholarly conceptualizations emerge, develop, and acquire significance.

The research problem addressed in this study consequently concerns the identification, systematization, and comparative interpretation of the **principal contribution points embodied in authors' conceptualizations of Digital Twins** within the five selected national contexts. The focus is not limited to contributions explicitly labelled as such by the respective authors. Rather, the study seeks to identify the conceptual elements through which individual authors extend, refine, integrate, or otherwise develop the existing understanding of Digital Twins. Such contributions may concern, inter alia, the functional scope of Digital Twins, their structural architecture, the relationship between physical and virtual entities, integration with artificial intelligence and data analytics, lifecycle management, predictive capabilities, optimization, and decision-support mechanisms.

Accordingly, **the aim of this article** is to identify, systematize and comparatively analyze the principal contribution points embodied in authors' conceptualizations of Digital Twins developed within the scholarly contexts of the United States, China, Bulgaria, Malaysia, and Indonesia, with particular emphasis on their significance for understanding Digital Twins as a driver of technological transformation.

To achieve this aim, the study pursues the following objectives:

a. to identify prominent scholarly conceptualizations of Digital Twins within the selected national research contexts;

b. to establish their principal conceptual characteristics and structural components;

c. to identify the distinctive contributions through which individual authors extend the existing scholarly understanding of Digital Twins;

d. to systematize these contributions according to their principal conceptual dimensions;

e. to undertake a comparative analysis of the identified contributions across the five national contexts;

f. to establish the similarities, differences, and potential correlations among the examined conceptualizations;

g. to assess the significance of the identified scholarly contributions for the development of Digital Twins as an instrument of technological transformation.

The **object of the study** is constituted by authors' conceptualizations of Digital Twins developed in scholarly publications and research contributions associated with the United States, China, Bulgaria, Malaysia, and Indonesia.

The **subject of the study** comprises the principal contribution points embodied in these conceptualizations, examined in terms of their conceptual originality, structural and functional characteristics, and potential to advance Digital Twins as an instrument of technological transformation.

In accordance with the stated aim, the study addresses the following principal **research questions**:

1. What are the principal scholarly conceptualizations of Digital Twins within the examined countries?

2. What distinctive contributions are embodied in each conceptualization?

3. In what ways does the scholarly originality of the respective conceptual approaches manifest itself?

4. What similarities and differences can be identified among the conceptualizations?

5. Which contributions are of greatest significance for advancing the understanding of Digital Twins as a driver of technological transformation?

Methodologically, the study adopts a comparative and conceptual approach to the examination of selected scholarly contributions. The analysis does not consider contributions solely on the basis of those explicitly

claimed by the respective authors; rather, it examines the content, structure, terminology, relationships, and distinctive characteristics of each conceptualization. This approach enables a distinction to be drawn between the established characteristics of Digital Twins identified in the broader literature and those elements that constitute specific forms of authorial conceptual development.

Particular attention is given to the **comparability of scholarly contributions**. Different authors may employ different terminology, emphasize different technological components, or approach Digital Twins from distinct disciplinary perspectives. Consequently, the comparative analysis is not based solely on terminological correspondence but on the functional and conceptual substance of the respective propositions. This approach makes it possible to identify both explicitly formulated and implicit contribution points and to establish their position within the broader evolution of the Digital Twin concept.

The scholarly significance of the present study lies in placing **authorial contribution at the center of the analysis**. Existing literature has established important conceptual and technological foundations for understanding Digital Twins (Grieves & Vickers, 2017; Kritzinger et al., 2018; Barricelli et al., 2019; Jones et al., 2020). The present study builds upon this foundation by shifting the analytical emphasis towards the comparative examination of how individual authors have contributed to the further conceptual development of the field.

In this respect, Digital Twins are approached not merely as a collection of technological capabilities but as an **evolving scholarly concept**, the development of which results from the accumulation, extension, refinement, and transformation of different authorial perspectives. By identifying and comparatively interpreting these contributions across the United States, China, Bulgaria, Malaysia, and Indonesia, the study seeks to establish a conceptual contribution framework demonstrating how individual scholarly conceptualizations extend the theoretical and applied understanding of Digital Twins and contribute to their emergence as a potential driver of contemporary technological transformation.

II. LITERATURE REVIEW

Douglas Thomas (2024) on the economic and investment assessment of Digital Twins. Thomas considers Digital Twins not only as a technological system, but as an investment decision, in which costs, benefits and conditions for economic efficiency must be compared. He develops a five-

step method for an investment analysis of Digital Twins and creates a model of the potential economic impact on production.

The main contributions of the author include:

✓ introducing a systematic approach to the economic assessment of Digital Twins;

✓ identifying the main categories of costs and benefits;

✓ considering the conditions under which investment in Digital Twin is economically justified;

✓ proposing a methodology for investment decision-making;

✓ quantifying the potential economic impact;

✓ laying the foundation for considering Digital Twin as a capital investment, and not just as an Artificial Intelligence project.

Ultimately, Douglas Thomas can be used as the main theoretical source for the financial model of digital twins.

The contribution of Omar Abbas, Nicola Moretti and Tim Broyd (2024) is particularly important for the lifecycle/value-based approach. The authors conduct a systematic review of the evidence on the benefits of Digital Twins and identify a significant scientific deficit: there are many described benefits and costs, but there are not enough comprehensive investment appraisal studies that can link these elements into a complete value proposition.

Their main contribution can be focused on:

✓ moving the analysis from technology benefits to whole-life value;

✓ considering value throughout the life cycle;

✓ identifying the discrepancy between declared and proven economic benefits;

✓ showing the need for a comprehensive investment appraisal framework;

✓ formulating a scientific niche for future empirical research.

This allows us to defend the thesis that the financial effectiveness of Digital Twins should not be measured only by the initial return on investment (ROI), but by the value generated throughout the lifecycle of the asset. This leads to:

Whole Life Value = Benefits (lifecycle) - Cost (lifecycle)

João Vieira, Nuno Marques de Almeida, João Poças Martins, Hugo Patrício and João Gomes Morgado (2024) take an important step from a general concept of value to a practical model for value-based investment decision-making.

The authors note that the literature and industry often claim that Digital Twins create value, but do not show convincingly how this value is realized and how it compares to alternative investments. They develop a value-based analysis for digital twin investments and test it through three infrastructure case studies.

The main contribution of the team is that the authors:

✓ introduce value-based analysis for Digital Twin investments;

✓ connect Digital Twins with traditional asset management investment planning;

✓ offer a common language for comparing digital and physical investments;

✓ demonstrate applicability through real case studies;

✓ show that Digital Twins should compete for financial resources with other investment alternatives.

This allows us to propose a transformation of the concept "Does Digital Twin have benefits?" to "Does Digital Twin Investment Create Higher Value Than Alternative Uses of the Same Capital?"

The contribution of Jun-Feng Yao, Yong Yang, Xue-Cheng Wang, and Xiao-Peng Zhang (2023) is that the financial model of digital twins is primarily technological and conceptual.

The authors provide a systematic review of Digital Twin technology and its applications and consider how digital representation overcomes the constraints of time, space, cost, and security and extends the functional value of physical objects.

Main contributions:

✓ systematize the development of Digital Twin;

✓ examine its architecture and technological characteristics;

✓ show the relationship between the physical object and its digital representation;

✓ identify application areas;

✓ emphasize the role of Digital Twin in optimization and value enhancement.

Yao et al. provide the technological prerequisite for the financial model. It is built on the logic:

Digital Representation → Real-Time Data → Analysis → Optimization → Economic Benefit

Therefore, their work can be used in defining the independent variable "Digital Twin capability".

Lukas Schweiger and Linard Barth (2023) focus on the operationalization of the concept of Digital Twin. They analyze 90 corporate definitions and develop a taxonomy of the properties and characteristics of Digital Twins. A significant result is the establishment of a distinction between academic definitions, which are more technologically oriented, and industrial definitions, which place greater emphasis on value-based properties.

The authors:

✓ develop a taxonomy of Digital Twin characteristics;

✓ systematically analyze corporate definitions;

✓ distinguish between technological and value-oriented characteristics;

✓ propose an application-oriented definition;

✓ create a basis for assessing different levels of Digital Twin sophistication.

The authors' contributions are particularly useful for constructing the variable: Digital Twin Maturity / Digital Twin Capability.

For example: presenting the concept as a variable function, namely:

DTM = f (Data, Connectivity, Synchronization, Analytics, Prediction, Simulation, Decision Support)

According to the authors, this variable can be empirically linked to: *Operational Performance → Financial Performance.*

Tharindu Karunaratne, Ikenna Reginald Ajiero, Rotimi Joseph, Eric Farr and Poorang Piroozfar (2025) provide the latest systematic review on the economic impact of Digital Twins, particularly in Architecture, Engineering and Construction (AEC). Through a PRISMA-based systematic review, the authors identify economic benefits, costs, barriers and factors that limit value realization. Particular attention is paid to high initial investments, integration complexity, regulatory constraints and lack of standardization. The author team:

✓ systematize the literature on economic impact;

✓ identify the main cost categories;

✓ examine the economic benefits;

✓ identify barriers to investment;

✓ show the sectoral dependence of the economic impact;

✓ highlight the need for more structured methods for economic evaluation.

This is particularly suitable for developing moderators and risk factors as a variable function of economic value, namely:

Economic Value = f (DT, Investment, Integration, Regulation, Standardization, Organization)

Ultimately, the synthesized matrix of scientific contributions to the financial concept can include: (Table 1)

Table 1
Synthesized matrix of scientific contributions

Authors	**Main practical and applied contribution**	**Role in the financial concept**
Thomas, D. (2024)	Economics and investment assessment of digital twins	Financial evaluation
Abbas, Moretti & Broyd (2024)	Whole-life value	Lifecycle economics
Vieira et al. (2024)	Value-based investment analysis	Investment prioritization
Yao et al. (2023)	Technological and functional framework	Digital twins (capability)
Schweiger & Barth (2023)	Taxonomy & DT characteristics	Digital twins (maturity)
Karunaratne et al. (2025)	Economic impact & barriers	Economic determinants & risks

Author's construction based on a specific database

Based on the specified literature, the financial concept of digital twins can be understood as an economic framework for assessing whether investment in a digital twin creates sufficient value over its life cycle to justify its implementation and operating costs. The main highlights of the financial concept for digital twins can be specified in the following points, namely:

a. Digital twins should be treated as an investment, not merely as an IT expense.

Their economic value arises from the ability to improve decision-making, reduce operational inefficiencies, prevent failures, optimize maintenance, and support better allocation of resources.

b. The financial benefit is primarily generated over the lifecycle.

Initial costs can include data acquisition, sensors and IoT infrastructure, software, modelling, integration, cybersecurity and implementation. However, these costs may be offset by savings during operation, maintenance and asset management.

c. The most important economic mechanism is the reduction of uncertainty and risk.

A digital twin can provide more accurate and timely information about an asset, allowing organizations to identify potential failures or

inefficiencies before they generate significant costs. Consequently, its financial value includes both direct savings and avoided costs.

d. Digital twins can increase the economic value of physical assets.

Better monitoring, predictive maintenance, optimization of asset utilization, and improved lifecycle planning can extend asset life and increase its productivity. Therefore, the digital twin should be evaluated not only by its own cost but also by its effect on the value and performance of the physical asset.

e. The economic effect is highly dependent on the application context.

There is no universal return on investment (ROI) for digital twins. The financial outcome depends on asset complexity, scale, data availability, implementation costs, organizational maturity, and the specific problems the digital twin is designed to solve.

f. Both tangible and intangible benefits must be considered.

Tangible benefits include lower maintenance costs, reduced downtime, energy savings, increased productivity and longer asset life. Intangible benefits include improved decision-making, better collaboration, knowledge retention, transparency and organizational learning.

g. A lifecycle approach is more appropriate than a short-term ROI calculation.

The financial assessment should consider the entire period from implementation through operation and eventual decommissioning. In that regard, indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback period, ROI, Total cost of ownership (TCO) and lifecycle cost savings can be used.

h. The value of a digital twin can increase as its use expands.

A twin initially created for monitoring, for example, may subsequently support predictive maintenance, asset optimization, investment planning, and strategic decision-making. This creates opportunities for additional economic benefits without necessarily requiring an entirely new digital infrastructure.

i. Data quality and interoperability are important financial factors.

Poor data quality, incompatible systems, insufficient integration, or high data maintenance requirements can significantly reduce the expected economic return. Thus, technological feasibility and financial feasibility are closely interconnected.

j. The financial concept should incorporate risk and uncertainty.

Since future savings and benefits are uncertain, investment decisions should not rely exclusively on a single ROI estimate. Scenario analysis,

sensitivity analysis, and risk-adjusted financial modelling are more appropriate.

Ultimately, the logical conclusion is: The literature suggests that the financial concept of digital twins is based on comparing the full lifecycle cost of creating, implementing, maintaining, and upgrading a digital twin with the economic value generated by improved asset performance and decision-making. In simplified form:

Financial value of a digital twin = Lifecycle economic benefits - Lifecycle costs

where benefits may include cost reduction + revenue/productivity gains + avoided losses + increased asset value, while costs include development + infrastructure + integration + data + operation + maintenance + cybersecurity and upgrading. Therefore, the economic justification for a digital twin should not be based solely on its technological capabilities. The key question is whether the digital twin generates measurable economic value greater than the resources required to create and operate it. This makes digital twin investment fundamentally a lifecycle value-management and investment-decision problem, rather than simply a technology-adoption decision.

III. RESEARCH METHODOLOGY

This research uses a systematic methodology, including bibliographic, bibliometric and qualitative content analysis. The main unit of analysis is the scientific publication, and a comparative analysis of the main frameworks for determining intellectual and conceptual contribution is made. The five countries studied, the USA, China, Bulgaria, Malaysia and Indonesia, constitute the comparative contextual dimension of the study.

1. Literature Search Strategy

A systematic search of scientific publications will be conducted using major academic databases, including Scopus, Web of Science, Google Scholar, ScienceDirect, SpringerLink and IEEE Xplore. The search will employ combinations of controlled and free-text keywords, including: digital twin; digital twins; digital twin technology; digital transformation; technological transformation; Industry 4.0; economic value; investment; digital twin adoption and digital twin framework. Boolean operators “AND” and “OR” will be used where appropriate, and NOT to refine the search strategy. Subsequently, searches will be conducted by country, using combinations such as “digital twins” in the US, “digital twins” in China, “digital twins” in the Islamic countries of Malaysia and Indonesia,

and “digital twins” in Bulgaria. A systematic search of scientific publications will be conducted using major academic databases, including Scopus, Web of Science, Google Scholar, ScienceDirect, SpringerLink and IEEE Xplore. (Table 2)

Table 2
Search for combinations of controlled and free keywords

First step	**Controlled and free-text keywords**
The search will employ combinations of controlled and free-text keywords, including:	✓ digital twin; ✓ digital twins; ✓ digital twin technology; ✓ digital transformation; ✓ technological transformation; ✓ Industry 5.0 in the context of Industry 4.0; ✓ economic value; ✓ investment; ✓ digital twin adoption and digital twin framework.

Author's construction based on a specific database.

2. Author-Centered Identification of Scientific Contributions

Following the initial literature search, an author-centered search procedure will be applied. The publication records of the principal authors identified in the initial search will be examined systematically in order to determine the scope and evolution of their research contributions. (Table 3)

Table 3
A search procedure focused on the publication records of the lead authors.

Step two	**Subject of analysis**
The analysis will consider:	✓ the number and chronology of relevant publications; ✓ the thematic orientation of the author's research; ✓ conceptual definitions and theoretical propositions; ✓ models and frameworks developed; ✓ methodological innovations; ✓ empirical findings; ✓ technological applications; ✓ economic and financial contributions; ✓ organizational and managerial implications; ✓ contributions to digital and technological transformation.

Note: This procedure enables the research to distinguish between an author's general involvement in digital-twin research and their specific scientific contribution to the conceptual development of the field. Author's construction based on a specific database.

3. Selection and Screening of Publications

The identified records will undergo a structured screening process consisting of: *Identification → removal of duplicates → title/abstract screening → full-text assessment → final inclusion.*

Table 4
Procedure of a structured review process

Step three	**A structured review process**
Publications will be included when they:	✓ are scientifically or institutionally credible; ✓ address digital twins as a substantive research topic; ✓ contribute to understanding technological, organizational, economic or transformational aspects of digital twins; ✓ provide sufficient information to identify the author's contribution; and ✓ are relevant to the conceptual and comparative objectives of the study.

Note: Duplicate publications, non-substantive references, promotional materials, and sources in which digital twins are mentioned only incidentally will be excluded. Author's construction based on a specific database.

4. Bibliometric Analysis

A bibliometric analysis will be conducted to establish the structure and development of the scientific field. Where appropriate, bibliometric visualization software such as VOSviewer and Bibliometrix/Biblioshiny may be employed. Bibliometric indicators will be interpreted as measures of research visibility and scholarly influence, rather than as direct measures of the scientific quality of an author's contribution. (Table 5)

Table 5
Bibliometric analysis of the structure and development of the scientific field.

Step four	**Aspects of biometric analysis**
The analysis will include:	✓ publication frequency and trends; ✓ citation patterns; ✓ author productivity; ✓ institutional and country affiliations; ✓ co-authorship relationships; ✓ keyword co-occurrence; ✓ citation and co-citation relationships; ✓ hematic development of the research field.

Author's construction based on a specific database.

5. Qualitative Content Analysis

Bibliometric results will be complemented by qualitative content analysis of the selected publications. The full texts will be systematically examined and coded according to the following contribution categories:

Table 6
Categories of contributing moments

Category	**Analytical focus**
Conceptual	Definitions, concepts, theories and conceptual models.
Technological	Internet of Things, Artificial Intelligence, sensors, data analytics, simulation, cloud/edge computing.
Methodological	Research methods, analytical models and proposed frameworks.
Economic	Costs, benefits, investment, ROI, productivity and value creation.
Organizational	Adoption, skills, management and organizational readiness.
Transformational	Process, product, service and business-model transformation.
Industrial	Applications in manufacturing, construction, infrastructure, energy and other sectors.
Institutional	Government policy, standards, regulation and national strategies.
Sustainability	Energy efficiency, resource optimization and environmental performance.

Author's construction based on a specific database.

6. Comparative Country Analysis

Following the analysis of individual publications and authors, the identified scientific contributions will be aggregated and compared across the five countries. (Table 7)

Table 7
Identified scientific contributions

Step six	**Summarizing and comparing scientific contributions**
The comparative analysis will examine:	✓ dominant research themes; ✓ degree of conceptual development; ✓ technological priorities; ✓ methodological approaches; ✓ economic and financial perspectives; ✓ industrial applications; ✓ institutional and policy dimensions; ✓ emerging research areas; ✓ identified gaps and limitations.

Note: The same analytical categories will be applied to each country to ensure comparability and methodological consistency. Author's construction based on a specific database.

7. Synthesis of the Conceptual Contribution Framework

The final stage will synthesize the findings into a Digital Twin Conceptual Contribution Framework.

Table 8
Findings in a conceptual contribution framework

Step Seven	**Summary of results**
The framework will establish relationships between:	Digital Twin Technologies ↓ Scientific and Conceptual Contributions ↓ Technological Applications ↓ Value Creation and Economic Effects ↓ Technological Transformation

Note: The national context will be incorporated as a comparative dimension influencing the nature and intensity of these relationships. The synthesis will therefore identify not only which authors have contributed to the field, but also what they have contributed, how their contributions have developed and how they differ across the five national research environments. Author's construction based on a specific database.

8. Validity and Reliability

The methodology will also distinguish between bibliometric influence and substantive scientific contribution, thereby avoiding the assumption that a highly cited publication necessarily represents the most significant conceptual contribution. (Table 9)

Table 9
Validity and Reliability

Step eight	**Validity and reliability measures**
Methodological reliability will be strengthened through:	✓ the use of multiple scientific databases; ✓ predefined search terms and selection criteria; ✓ systematic documentation of the search and screening process; ✓ cross-verification of bibliographic information; ✓ triangulation of bibliometric and qualitative findings; ✓ consistent application of the coding framework; ✓ comparison of academic publications with authoritative institutional sources where appropriate.

Author's construction based on a specific database.

Ultimately, we can draw up the following methodological summary. The methodological logic of the research can be expressed as: (Table 10)

Table 10
Methodological summary of the results

a. Systematic database search	b. Academic formulation
Identification of relevant publications Author-centered publication search Screening and selection Bibliometric analysis Qualitative content analysis Classification of scientific contributions United States - China - Bulgaria – Malaysia - Indonesia comparison Synthesis of the Conceptual Contribution Framework Identification of research gaps and future directions.	**Firstly,** the research employs a systematic bibliographic, bibliometric and qualitative content-analysis methodology to investigate the scientific contribution of digital-twin research to technological transformation. The scientific publication constitutes the primary unit of analysis, while authors are examined as the principal source of intellectual and conceptual contribution. **Secondly**, publications are systematically identified through major international scientific databases using predefined keywords and boolean search strategies, followed by author-specific searches to establish the broader research trajectories of the principal contributors. The selected publications are subjected to bibliometric analysis to identify patterns of scientific production, citation, collaboration and thematic development, and to qualitative content analysis to classify contributions according to conceptual, technological, methodological, economic, organizational, transformational, industrial, institutional and sustainability dimensions. **Thirdly**, the identified contributions are subsequently compared across the United States, China, Bulgaria, Malaysia and Indonesia using a common analytical framework. The synthesis of these findings provides the basis for constructing a comparative Digital Twin Conceptual Contribution Framework and for identifying the principal theoretical, methodological and practical gaps in the existing body of knowledge.

Author's construction based on a specific database.

IV. DATA ANALYSIS & RESULTS

With regard to the emergence of the concept of digital twins, the following key variants stand out, namely:

1. David Gelernter as a pioneer of the concept

In 1991, David Gelernter published Mirror Worlds, in which he developed the idea of software models capable of representing and reflecting the real world through data from the physical environment. Some historical reviews consider this to be an intellectual precursor to the Digital Twin.

(Gelernter, D. 1991). However, this is a prehistory of the concept, not the Digital Twin in its modern technological sense.

2. Michael Grieves - the initial concept, 2002

In academic literature, Michael Grieves is most often cited as the author who formalized the modern concept of the Digital Twin in 2002 in the context of Product Lifecycle Management (PLM) at the University of Michigan. Initially, he did not use the name Digital Twin. The model was presented as the "Conceptual Ideal for PLM", and later received the name Mirrored Spaces Model, and then Information Mirroring Model. (Grieves, M. 2006). Grieves' model contains the three fundamental components that still form the basis of Digital Twin definitions today:

Physical Space + Virtual Space + Data Connection

That is: *physical object ↔ digital representation ↔ flow of information between them.*

Grieves himself later confirmed that the basic concept dates back to 2002, although the terminology changed in the following years.

3. John Vickers coined the term "Digital Twin", 2010

John Vickers, an engineer and technologist at NASA, is credited with introducing/naming the concept as "Digital Twin" in 2010 within the NASA Technology Roadmap. NASA itself cites Vickers as the person credited with coining the term in 2010. The National Academies also cite the term "digital twin" as appearing around 2010 in NASA's technology planning, co-led by John Vickers. (Vickers, J.H. et al. 2010); (Grieves, M. and Vickers, J. 2016). Therefore, Michael Grieves formalized the concept; John Vickers coined the term "Digital Twin".

4. NASA contributed before Grieves

NASA has used the principle of physical/simulation "twinning" since Apollo, including Apollo 13 in 1970. On Earth, physical and computer simulations of the spacecraft were used to replicate conditions and test possible solutions to the accident. Modern reviews identify this as one of the earliest practical implementations of the Digital Twin principles. NASA itself traces the origins of the Digital Twin to the Apollo program and emphasizes that this practice predates modern terminology by decades. We can therefore distinguish between the following periods: (Table 11)

Table 11
Contributing moments when the concept emerged

Period	Author/Institution	Contribution	Conceptual significance
1960s - 1970s	NASA	Early practical use of physical and simulation "twins"	NASA's space programs
1991	David Gelernter	The idea of software models that reflect the real world in Mirror Worlds	Intellectual predecessor
up to 2000	NASA	Simulation and physical "twinning"	Practical predecessors
2002	Michael Grieves	Formalizing the modern concept in PLM	Formalization of the concept
2002 -2006	Michael Grieves	Conceptual Ideal for PLM → Mirrored Spaces Model → Information Mirroring Model	Relationship with the life cycle
2010	John Vickers / NASA	Introduction to the term "Digital Twin"	Terminological validation
2012	NASA / Glaessgen, Stargel, Shafto and others.	Development and formalization of a Digital Twin for aerospace engineering	Establishing the term "Digital Twin"
2014	Grieves	Digital Twin in manufacturing	Expansion into virtual production
2020 -2026	Contemporary authors - Grieves, M. (2016); Yao, J.-F. et al. (2023) & Schweiger, L. and Barth, L. (2023)	AI, IoT, simulation, analytics	Integrated cyber-physical system

Author's construction based on a specific database.

5. The evolution of scientific understanding

Following its initial formalization, the concept has expanded considerably. Contemporary research views the Digital Twin as an integrated cyber-physical system that combines a physical object, a digital model, real-time data, analytical methods and feedback mechanisms.

Yao et al. (2023) systematize the development of the technology and demonstrate the expansion of its application beyond manufacturing into a wide range of industrial and scientific fields. Schweiger and Barth (2023), for their part, demonstrate that there is considerable diversity in the literature regarding the definitions and characteristics of the Digital Twin. This suggests that the concept should not be defined solely by the presence of a digital model, but rather by the degree of connectivity, synchronization, data exchange, analytical capability and functional integration with the physical object.

From all that has been said so far, the following generalized conceptual definition can be proposed: A digital twin is a dynamic digital representation of a physical object, process, or system that, through a bidirectional or functionally integrated information connection, uses data from the physical environment for monitoring, analysis, prediction, simulation, and decision support throughout the life cycle of the object.

This definition is more stringent than defining a Digital Twin solely as a "virtual copy," as it includes dynamism, data, interconnection, analytical capability, and lifecycle management.

References:

1. Abbas, O. H., Moretti, N., & Broyd, T. (2024). Assessing the Benefits of Digital Twins Towards the Formulation of Whole Life Cycle Value Propositions: A Systematic Review. In Proceedings of the 2024 European Conference on Computing in Construction. European Council on Computing in Construction (EC3). https://doi.org/10.35490/EC3.2024.304.
2. Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on Digital Twin: Definitions, characteristics, applications, and design implications. IEEE Access, 7, 167653-167671. https://doi.org/10.1109/ACCESS.2019.2953499.
3. Batty, M. (2018). Digital twins. Environment and Planning B: Urban Analytics and City Science, 45(5), 817-820. https://doi.org/10.1177/2399808318796416
4. Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban Digital Twins for smart cities and citizens: The case study of Herrenberg, Germany. Sustainability, 12(6), 2307. https://doi.org/10.3390/su12062307.
5. Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. IEEE Access, 8, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358.
6. Grieves, M. (2014) Digital Twin: Manufacturing Excellence through Virtual Factory Replication. White Paper. 1-7.
7. Grieves, M. & J. Vickers (2016) Origins of the Digital Twin Concept. Florida Institute of Technology. 1-7, DOI: 10.13140/RG.2.2.26367.61609.
8. Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), Transdisciplinary perspectives on complex systems: New findings and approaches (pp. 85-113). Springer. https://doi.org/10.1007/978-3-319-38756-7_4.
9. Gelernter, D. (1991) Mirror Worlds: Or the Day Software Puts the Universe in a Shoebox...How It Will Happen and What It Will Mean. New York: Oxford University Press. 15-36, DOI: 10.1093/oso/9780195068122.001.0001.

10. Grieves, M. (2006) Product Lifecycle Management: Driving the Next Generation of Lean Thinking. New York: McGraw-Hill, 1-290.
11. Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36-52. https://doi.org/10.1016/j.cirpj.2020.02.002.
12. Karunaratne, T., Ajiero, I. R., Joseph, R., Farr, E., & Piroozfar, P. (2025). Evaluating the Economic Impact of Digital Twinning in the AEC Industry: A Systematic Review. Buildings, 15(14), 2583, 1–29. https://doi.org/10.3390/buildings15142583.
13. Kaiblinger, A., & Woschank, M. (2022). State of the art and future directions of Digital Twins for production logistics: A systematic literature review. Applied Sciences, 12(2), 669. https://doi.org/10.3390/app12020669.
14. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474.
15. Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of Digital Twin in CPS-based production systems. Procedia Manufacturing, 11, 939-948. https://doi.org/10.1016/j.promfg.2017.07.198.
16. Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and Industry 4.0: 360-degree comparison. IEEE Access, 6, 3585-3593. https://doi.org/10.1109/ACCESS.2018.2793265.
17. Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital Twin: Values, challenges and enablers from a modeling perspective. IEEE Access, 8, 21980-22012. https://doi.org/10.1109/ACCESS.2020.2970143.
18. Schweiger, L., & Barth, L. (2023). Properties and Characteristics of Digital Twins: Review of Industrial Definitions. SN Computer Science, 4, 436, 1–25. https://doi.org/10.1007/s42979-023-01937-4.
19. Schweiger, L. and Barth, L. (2023) Properties and Characteristics of Digital Twins: Review of Industrial Definitions, SN Computer Science, 4, 436. DOI: 10.1007/s42979-023-01937-4.
20. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415.
https://doi.org/10.1109/TII.2018.2873186.
21. Tao, F., Qi, Q., Wang, L., & Nee, A. Y. C. (2019). Digital twins and cyber–physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison. Engineering, 5(4), 653-661. https://doi.org/10.1016/j.eng.2019.01.014.

22. Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2018). Digital twin driven prognostics and health management for complex equipment. CIRP Annals, 67(1), 169-172. https://doi.org/10.1016/j.cirp.2018.04.055.
23. Thomas, D. (2024). Economics of Digital Twins: Costs, Benefits, and Economic Decision Making. NIST Advanced Manufacturing Series, NIST AMS 100-61. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.AMS.100-61.
24. Vieira, J., Almeida, N. M. de, Poças Martins, J., Patrício, H., & Morgado, J. G. (2024). Analysing the Value of Digital Twinning Opportunities in Infrastructure Asset Management. Infrastructures, 9(9), 158. https://doi.org/10.3390/infrastructures9090158.
25. Vickers, J.H. et al. (2010) Technology Area 12: Materials, Structures, Mechanical Systems, and Manufacturing Technology Road Map. NASA Office of Chief Technologist, pp. 1-100.
26. Yao, J.-F., Yang, Y., Wang, X.-C., & Zhang, X.-P. (2023). Systematic Review of Digital Twin Technology and Applications. Visual Computing for Industry, Biomedicine, and Art, 6(1), 10, 1–20. https://doi.org/10.1186/s42492-023-00137-4.
27. Yao, J.-F. et al. (2023) Systematic review of digital twin technology and applications, Visual Computing for Industry, Biomedicine, and Art, 6, 10. DOI: 10.1186/s42492-023-00137-4.

A COMPARATIVE ANALYSIS OF CONCEPTUAL FRAMEWORKS FOR DIGITAL TWINS IN THE UNITED STATES, CHINA, MALAYSIA, INDONESIA AND BULGARIA - PART II

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Abstract: *Digital Twins have emerged as a significant component of contemporary digital transformation; however, their conceptual development and strategic application differ substantially across national contexts. This study provides a comparative analysis of the evolution of Digital Twin conceptual frameworks in the United States, China, Malaysia, Indonesia, and Bulgaria. The analysis examines the historical, technological, institutional, industrial, and economic dimensions underlying the development of national Digital Twin models, with particular attention to their integration with artificial intelligence, smart manufacturing, lifecycle management, urban digitalization, and standardization. The comparative findings indicate the emergence of distinct national trajectories. The United States model is primarily characterized by an engineering-, lifecycle-, and industrial-optimization orientation, evolving from physical system modelling toward integrated manufacturing and standardized Digital Twin ecosystems. In contrast, the Chinese model demonstrates a broader digital transformation and governance orientation, extending from intelligent manufacturing to smart cities, national standardization, and integrated digital governance. Malaysia and Indonesia demonstrate emerging application-oriented trajectories, while Bulgaria reflects a developing model shaped by Building Information Modelling, smart cities, public administration, energy efficiency, and Industry 4.0. The study demonstrates that Digital Twins should not be regarded as a uniform technological paradigm but as context-dependent instruments of technological transformation. Their effectiveness is influenced by technological maturity, institutional capacity, investment conditions, human capital, regulatory frameworks, and national strategic priorities. The findings provide a comparative framework for understanding national Digital Twin development and identify strategic considerations for advancing Digital Twin adoption in emerging technological environments. To support their arguments and research findings, the author presents four appendices. These contain a comparative analysis of the author's studies*

regarding the leaders of the digital twin concept in the United States and China.

Keywords: *Comparative analysis, national innovation systems, digital governance, intelligent manufacturing, smart cities, technological development, standardization, institutional capacity, emerging economies, technological catch-up*

V. THE CONCEPT OF DIGITAL TWINS IN THE UNITED STATES

Modern digital twin researchers in the United States highlight the following stages of development, namely:

First stage: Historical and Theoretical Background

The development of the concept of Digital Twins in the United States is a consistent process of transition from computer modeling and simulation to dynamic, interconnected digital representations of physical objects, processes and systems. In the American scientific and technological context, the concept was formed at the intersection of aerospace research, engineering modeling, Product Lifecycle Management (PLM), technical condition monitoring systems and later - the Internet of Things, artificial intelligence and big data analysis.

It is necessary to make a distinction between the historical technological background of the Digital Twin and the formulation of the concept itself. Computer modeling, simulation and the use of digital representations of physical systems precede the term Digital Twin. In this sense, it would not be methodologically correct to claim that one specific institution "invented" the entire concept. It is more correct to assume that it was formed gradually through the accumulation of engineering and scientific practices with subsequently received conceptual and terminological accuracy.

Second stage: Conceptualizing the Digital Twin

In modern literature, Michael Grieves is associated with the early conceptualization and popularization of the idea of a digital twin in the context of product lifecycle management. The essential characteristic of this approach is the existence of an interrelationship between the physical product, its digital representation, and the data that describe its state and development. Therefore, the conceptual development can be represented by the following sequence:

Physical Object ↔ Digital Representation ↔ Data

This conceptual structure forms the basis for the subsequent development of the Digital Twin as a dynamic system, rather than as a static digital model.

Third stage: NASA and U.S. Air Force: Moving to the Lifecycle of the Physical Object

A significant stage in the development of the American concept is associated with aerospace research. Glaessgen and Stargel (2012) formulate the Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles, proposing a paradigm in which high-precision digital simulation is integrated with systems for monitoring the technical condition, maintenance history and available operational data of the specific aircraft (Glaessgen and Stargel, 2012, pp. 1-14). The official NASA record confirms that the publication was presented in 2012 at the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. Here, a fundamental transition is made from digital modeling to a dynamic digital representation of a specific physical asset. The digital twin is no longer seen as just a pre-created model, but as a system that is updated with information about the real state of the physical object. This concept can be represented as:

Digital Model + Operational Data + Health Monitoring + Simulation = Digital Twin

The special significance of the American aerospace approach lies in its orientation to the entire lifecycle of the physical asset - from design and production to operation, maintenance and decommissioning.

Fourth stage: Digital Twin and Lifecycle Management

In the Glaessgen and Stargel paradigm, the Digital Twin is used to create a digital equivalent that "follows" the lifecycle of the physical object. This is particularly important for systems with high capital value, complex construction and high failure costs. From here the following logic is formed:

Design → Manufacturing → Operation → Maintenance → End-of-Life

where the information generated in each phase can be used in the following phases.

This approach lays the foundation for the later development of the Digital Thread concept, in which information flows between the different stages of the lifecycle are integrated into a single digital environment.

Fifth stage: Transition to Smart Manufacturing

After aerospace applications, the concept gradually expanded to manufacturing. The role of the National Institute of Standards and Technology (NIST) is particularly significant, as it begins to systematically develop a methodological and standardization basis for the use of the Digital Twin in the manufacturing sector.

Shao and Helu (2020) emphasize that the Digital Twin has the potential to become a core technology for smart manufacturing, but at the same time there is significant conceptual uncertainty regarding its content, characteristics and practical implementation (Shao and Helu, 2020, pp. 105-107). The article was published in Manufacturing Letters, Volume 24, pp. 105-107, with DOI 10.1016/j.mfglet.2020.04.004. This stage is essential, as a Digital Twin is starting to be considered not just as an engineering simulation tool, but as a component of a smart manufacturing system. According to Shao and Helu (2020), the need for a common framework is related to the possibility of Digital Twin components being reused, combined and functioning in different manufacturing contexts (Shao and Helu, 2020, pp. 105-107).

Sixth stage: NIST and Digital Twin Standardization

A particularly characteristic feature of the American model is the transition from separate research and industrial applications to a standardized architecture. NIST actively participated in the development and promotion of the ISO 23247 - Digital Twin Framework for Manufacturing, which was subsequently published in 2021 as a series of international standards (NIST, 2026). Shao (2021) examines specific scenarios for implementing Digital Twins based on ISO 23247 and emphasizes the importance of common terminology, architecture, and rules for implementing Digital Twins in a manufacturing environment (Shao, 2021). ISO 23247 consists of four main components that address general principles, reference architecture, digital representation, and information exchange. This structure aims to create a common foundation for the development of use case-specific Digital Twin systems (Shao, 2021, pp. 8-10). Therefore, the American model can be represented as:

Research → Application → Framework → Standardization → Interoperability

Seventh stage: Digital Twin as a system for monitoring, prediction and optimization

The modern American concept is moving away from the simplistic understanding of the Digital Twin as a “digital copy”. NIST defines digital

twins as synchronized virtual models that can support the representation, diagnosis, prediction and optimization of manufacturing operations (NIST, 2026).

From this point of view, the Digital Twin can be represented as:

Representation + Synchronization + Diagnosis + Prediction + Optimization

This formulation is particularly important for the economic interpretation of this technology. If the Digital Twin can predict a probable failure or deviation, the organization gets the opportunity to take preventive action. Therefore:

Prediction → Preventive Action → Risk Reduction → Cost Savings

Thus, technological functionality is transformed into economic value.

Eighth stage: Digital Twin and Artificial Intelligence

The modern American approach is characterized by the integration of Digital Twins with smart sensors, Industrial Internet of Things (IIoT), artificial intelligence, machine learning, modeling and simulation. NIST defines this technological integration as the basis for the development of reliable and interoperable Digital Twins in modern manufacturing (NIST, 2026). The technological architecture can be represented:

Sensors + IIoT + AI/ML + Simulation + Data → Digital Twin

This allows the Digital Twin to function as an analytical and predictive system, and not just as a visual or informational representation.

Ninth stage: From Digital Twin of a machine to Digital Twin of a manufacturing system

The next stage in the American model is the integration of individual digital twins into larger systems.

For example:

DT machine + DT process + DT factory → DT manufacturing system

This means that optimization is no longer performed only at the level of an individual asset, but at the level of an interconnected system of assets and processes. NIST considers the creation of reference architectures and standards that enable data integration between machines, production processes and different stages of the lifecycle to be a key task (NIST, 2026).

Tenth stage: Economic dimension

From the perspective of this dissertation research, the most essential aspect of the American concept is the transition to measurable economic value. NIST defines the potential effects of the Digital Twin in production by increasing productivity, improving quality and reducing production costs (NIST, 2026). Therefore, the economic mechanism can be represented:

Digital Twin → Better Information → Better Prediction → Better Decision → Economic Value

The financial effect can arise in several directions: reducing unplanned downtime; reducing maintenance costs; reducing defective production; optimizing production capacity; reducing resource consumption; optimizing capital investments; reducing operational risk. This allows the Digital Twin to be included in a financial model through indicators such as: NPV, IRR, ROI, TCO, Payback Period, and in public or infrastructure applications, social return on investment (SROI) and avoided-cost analysis can be added.

Eleventh stage: Modern American model

At this stage, the American concept already goes beyond the traditional production environment. NIST indicates applications of Digital Twins in manufacturing, construction, smart cities, healthcare and other sectors, with the common characteristic being the use of the digital twin for monitoring, forecasting, optimization and control (Shao, Kibira and Frechette, 2024). In parallel, NIST is developing a Digital Twin Testbed, through which the reliability, interoperability, verification, validation and uncertainty quantification of Digital Twin systems are studied (NIST, 2026). Therefore, the modern American paradigm can be presented as follows:

AI + IIoT + Simulation + Standards → Digital Twin → Prediction → Optimization → Decision Support → Economic Value

The following more important conclusions logically follow:

Firstly, this periodization shows that the American conceptual model is characterized by an evolution from engineering simulation to a standardized digital infrastructure for management and economic optimization.

Secondly, the United States is the leader among the leading research centers for the conceptual, applied, and standardization development of the digital twin.

Thirdly, the historical contribution of NASA and the US Air Force is related to the transformation of the digital model into a tool for tracking and managing the lifecycle of complex physical assets, while NIST contributes to the systematization of the concept within the framework of smart manufacturing, interoperability, measurement science, and standardization.

All in all, it can be summarized as follows:

The American scientific contribution to the development of the Digital Twin concept can be characterized as a progressive transition from a product lifecycle management paradigm towards an integrated cyber-physical, predictive and lifecycle-oriented framework. Michael Grieves provided the foundational conceptual architecture by introducing the interrelationship between the physical entity, its virtual representation and the data exchange linking the two. John Vickers and NASA subsequently contributed to the institutionalization and terminology of the concept, while Edward Glaessgen, David Stargel and the broader NASA research community substantially advanced its engineering formalization through the integration of high-fidelity metaphysics simulation, sensor data, historical information, health-management systems and fleet-level knowledge. Consequently, the American school established the conceptual and technological foundations for the contemporary understanding of the Digital Twin as a dynamic, data-driven and predictive representation of a physical system throughout its lifecycle.

VI. THE DIGITAL TWIN CONCEPT IN CHINA: EVOLUTION, INSTITUTIONALIZATION AND ECONOMIC SIGNIFICANCE

The development of the Digital Twin concept in China follows a specific trajectory, driven by the combination of technological innovation, government policy, industrial digitization, and large-scale transformation of the urban environment. Unlike the American model, in which the historical development of the concept is closely related to the aerospace industry, the lifecycle management of complex technical systems, and subsequently smart manufacturing, the Chinese model is characterized by a stronger institutional and infrastructural integration of the Digital Twin into the national digital transformation policy.

In Chinese scientific and management discourse, the concept of a “Digital Twin City” has acquired particular importance. It is developing as the

next stage in the evolution of the Smart City, in which the digital environment does not only perform the function of information and communication infrastructure, but also becomes a dynamic model of the physical urban system. Zhang et al. (2022, pp. 2-11) define Digital Twin City as a new direction and a new trajectory in the development of smart cities and propose a conceptual framework including four technological characteristics, three main visions and nine development elements.

Therefore, the Chinese concept can be presented as a transition:

Smart City → Digital Twin City → Digital Governance

This transition is of particular importance for the academic study of Digital Twins, as it shows the expansion of the concept from digital modeling of a single asset to digital representation, simulation and management of complex socio-economic systems.

1. Theoretical basis of the Chinese concept

Chinese scientific literature considers Digital Twin as a cyber-physical concept based on the integration of physical objects, digital models, data and communication networks. Wu et al. (2023) systematize the modern concept through four interconnected dimensions - data, models, networks and applications - and emphasize the need for continuous interaction between physical and virtual space. In this context, Digital Twins should not be identified with the traditional digital model. The latter represents the characteristics of an object, while the digital twin implies a dynamic relationship between the physical object and its digital representation. This difference can be formalized as follows:

Digital Model ≠ Digital Twin

while:

Physical Entity ↔ Data ↔ Digital Model, represents the fundamental structure of the Digital Twin.

Hence the main scientific characteristic of the Chinese approach - the integration of data, models and infrastructure into a single digital environment.

2. Digital Twin and Intelligent Manufacturing

The first major direction of Chinese development is related to intelligent manufacturing. Digital Twin integrates with Industrial Internet, Internet of Things, cloud computing, big data, artificial intelligence and

advanced simulation. In the manufacturing context, the digital twin can simultaneously perform the following functions: monitoring; diagnostics; forecasting; simulation; optimization; management. Therefore, the functional architecture can be represented as:

IoT + Industrial Data + AI + Simulation → Industrial Digital Twin

3. The transition from the "Smart city" to the "Digital twin of the city"

However, the most characteristic contribution of the Chinese model is the development of the Digital Twin City concept. Zhang et al. (2022, pp. 2-11) argue that the Digital Twin City represents a new stage in the development of the Smart City. The authors formulate the "4+5" framework, through which the technological characteristics, visions and main elements of the urban digital twin are systematized. Particular attention is paid to the need to improve data management and develop sustainable business models for the Digital Twin City. Here a fundamental conceptual change is observed: Smart City = Digital Services while:

Digital Twin City = Data + Model + Simulation + Prediction + Decision Support

Therefore, the Digital Twin City is not simply a more advanced GIS or Smart City platform. It implies a dynamic virtual and physical connection that allows urban processes to be monitored, modeled, simulated and optimized.

4. Institutionalization through national standardization

Significant evidence of the institutional development of the concept is the adoption of the national standard GB/T 45109.1-2024 - Smart city - City digital twin - Part 1: Technical reference architecture.

The standard was published on December 31, 2024, and entered into force on July 1, 2025. It defines a technical reference architecture for a digital twin of a city and covers intelligent infrastructure, data resources, digital engines, digital twin services, security and operational management. From an academic perspective, this is paramount, since it demonstrates the transition:

Research Concept → Pilot Application → Technical Framework → National Standard

Therefore, China is not only implementing the Digital Twin, but also codifying its architecture in a national standardization system.

5. Architectural nature of the Chinese Digital Twin City

The Chinese City Digital Twin standard considers the architecture as a set of interconnected technological and management components. The official standard defines requirements for data, information infrastructure, common services, twin services, interfaces, security and operational management. This allows the architecture to be conceptually presented as:

Infrastructure + Data + Digital Engine + Twin Services + Security + Operations

This model is significantly broader than the traditional understanding of a digital model. In it, the Digital Twin functions as a digital operating environment for the physical system.

6. Integration of Digital Twin with Artificial Intelligence

The modern Chinese model increasingly closely connects Digital Twins with artificial intelligence (AI) and machine learning. The technological sequence can be represented:

IoT → Big Data → AI → Digital Twin → Prediction → Optimization

This allows Digital Twins to evolve from a descriptive to a predictive and prescriptive system. This transformation is particularly important for economic analysis, because predictive ability creates the opportunity to reduce uncertainty in investment and management decisions.

7. Standardization evolution in 2024-2026

The current stage shows the acceleration of Chinese standardization.

In addition to GB/T 45109.1-2024 for City Digital Twin, GB/T 45873-2025 - Information technology - Digital twin for workshop - Reference architecture was published in 2025, which came into effect on January 1, 2026. In parallel, GB/T 45616.2-2025 - Digital twin framework for manufacturing - Part 2: Reference architecture was also published, which came into effect on March 1, 2026. This shows that Chinese standardization is already developing in parallel directions:

City Digital Twin + Manufacturing Digital Twin + Workshop Digital Twin

Thus, a Digital Twin is gradually becoming a systemic national technological paradigm.

In summary form, a comparative analysis of China and the United States in the development of digital twin concepts can be presented as follows:

From a comparative perspective, two distinct trajectories can be identified.

a. The American model can be broadly defined as:

Digital Twin as an engineering, lifecycle and industrial optimization paradigm.

b. The Chinese model can be defined as:

Digital Twin as a national digital transformation and governance paradigm.This distinction is analytical rather than absolute, as City Digital Twins do exist in the United States, whilst industrial Digital Twins are present in China.

c. The difference lies primarily in the focus of development:

United States: *Engineering → Industry → Standardization*

China: *Digitalization → Industry → City → Governance*

Academically, the Chinese Digital Twin model can be defined as an institutionally supported and infrastructure-oriented paradigm of digital transformation. Its distinguishing feature is the integration of Digital Twins with industrial digitalization, urban development, national standardization and public management. An important point is that China no longer treats Digital Twins solely as an experimental technology. The adoption of GB/T 45109.1-2024 for the City Digital Twin, effective from July 1, 2025, as well as the subsequent standards for manufacturing and workshop Digital Twins, indicate a process of formalization and institutionalization of the concept. From the perspective of this study, the most important conclusion is the following:

Chinese Digital Twin = Technology + Infrastructure + Industry + Urban Governance + Standardization + Economic Value

Therefore, the Chinese experience is particularly relevant for the development of a financial concept for the Digital Twin, as it allows the analysis to be taken beyond the level of return of an individual technological asset and to encompass the economic efficiency of entire urban, industrial and public systems.

VII. THE DEVELOPMENT OF THE DIGITAL TWIN CONCEPT IN ISLAMIC COUNTRIES - MALAYSIA AND INDONESIA

1. Development of the Digital Twin Concept in Malaysia

The development of the Digital Twin concept in Malaysia should be seen in the context of the broader national policy for digital transformation, Industry 4.0 and modernization of the construction and manufacturing sector. Of particular importance are: the development of Building Information Modelling (BIM), the integration of IoT technologies, cloud computing and the subsequent transition to dynamic digital models of physical assets.

The initial stage is related to the introduction and institutionalization of BIM in the construction sector. In this context, BIM can be seen as an important technological prerequisite for the development of the Digital Twin, as it creates a structured digital representation of the physical object and allows the accumulation and management of information throughout the different phases of its lifecycle. The Malaysian Construction Industry Development Board (CIDB) defines BIM as one of the main tools for the digitalization of the construction sector and links its application to increasing productivity and lifecycle management of construction sites (CIDB Malaysia, 2020, p. 14).

The next stage is the adoption of the Industry 4 WRD: National Policy on Industry 4.0 in 2018. The policy aims to accelerate the digital transformation of the manufacturing sector and related services and includes technology solutions related to automation, connected systems, data analytics and integration between the physical and digital environments (MITI, 2018). The policy was officially launched on October 31, 2018 with the aim of promoting the digital transformation of manufacturing and related services in Malaysia (Ministry of International Trade and Industry, 2018, pp. 14-18).

At this stage, the Digital Twin is not yet an isolated national technology policy, but is developing as part of the broader Industry 4.0 ecosystem. This is of particular importance, as it creates the necessary infrastructural and organizational foundation for the integration of physical assets, sensor systems, data and digital models.

In the next stage, a Digital Twin begins to be considered as a standalone technology for managing physical assets. According to CIDB, a digital twin enables the creation of a dynamic digital representation of a physical asset by integrating BIM, IoT and sensor data. This integration enables

real-time monitoring, anomaly detection and predictive maintenance (Construction Industry Development Board Malaysia, CIDB (2025).

From an economic perspective, the significance of this transformation lies in the ability of the Digital Twin to reduce unplanned downtime, optimize technical maintenance and extend the service life of equipment. Therefore, technological transformation is gradually becoming a mechanism for generating economic efficiency.

Large infrastructure projects are of particular importance. In large-scale projects in Malaysia, the Digital Twin is associated with the use of BIM, GIS, IoT, cloud technologies and other digital tools. In this way, the digital model ceases to be just a visualization tool and becomes an information infrastructure for monitoring and managing the physical infrastructure.

As a result, the development of the concept in Malaysia can be represented as a sequence:

BIM → Industry 4.0 → IoT Integration → Digital Twin → Smart Infrastructure

This sequence shows that the Malaysian model is characterized by gradual technological and institutional evolution.

2. Development of the Digital Twin Concept in Indonesia

The development of Digital Twin in Indonesia has similar technological prerequisites, but is characterized by a stronger connection between Industry 4.0, digital governance and the development of smart cities.

One of the important scientific contributions in the Indonesian context is the study by Husni, Gaol, Supangkat and Ranti (2022), which examines the possibility of applying the Digital Twin concept in Indonesia Digital Government Systems (IDGS). The authors propose a framework for integrating Digital Twin with IT governance mechanisms in the public sector (Husni et al., 2022, pp. 45-52). This approach is of particular importance because it expands the scope of application of Digital Twin beyond manufacturing. The concept is beginning to be seen as a possible tool for managing the digital state, in which information about systems and processes can be modeled, monitored and used to improve management decisions (Husni et al., 2022, pp. 45-52). Thus, a specific direction of development is being formed in Indonesia:

Industry 4.0 → Cyber-Physical Systems → Digital Government → Smart City

This trajectory distinguishes the Indonesian model from the traditional understanding of the Digital Twin as a predominantly production technology.

2.1. Digital Twin and the development of Nusantara

The most significant contemporary example of the application of the concept in Indonesia is the development of Nusantara (IKN) - the new capital of the country. In the scientific study by Rachmawati et al. (2024) the Digital Twin is considered in the context of the future development of Nusantara as a smart and sustainable city. The authors use empirical data obtained through interviews, focus groups and surveys among experts and representatives of institutions involved in urban and ICT planning (Rachmawati et al., 2024, pp. 4613-4621). According to the authors, Digital Twins can support the monitoring and analysis of infrastructure characteristics and the use of urban resources, including the management of transport, water, energy and waste (Rachmawati et al., 2024, pp. 4615-4618). A significant result of the study is the conclusion that the application of Digital Twins in Nusantara is still in an early stage of development, but the technology has the potential to support the construction of a smarter, sustainable and inclusive urban environment (Rachmawati et al., 2024, pp. 4619-4621).

This is particularly important from the perspective of the dissertation research, because Nusantara provides an opportunity for Digital Twins to be implemented not only for managing existing infrastructure, but also in the process of designing, building and developing an urban system.

In this way, the model arises:

Digital Model → Urban Digital Twin → Real-time Monitoring → Simulation → Urban Decision Support

3. Comparative analysis between the two Islamic countries

A comparison of the two countries shows significant similarities, but also differences in the institutional logic of development. (Table 12)

From a comparative perspective, it can be assumed that Malaysia is developing the Digital Twin primarily from a manufacturing-infrastructure basis to urban governance, while Indonesia is developing the concept simultaneously from Industry 4.0 to Digital Government and Urban Digital Twin. This difference has significant implications for financial valuation. In the Malaysian model, the expected value can be primarily linked to cost reduction, productivity, maintenance and asset management. In the Indonesian model, the economic value has a broader dimension, including public governance efficiency, urban infrastructure, resource use and sustainable development (Husni et al., 2022, pp. 45-52; Rachmawati et al., 2024, pp. 4615-4621).

Table 12
Comparative analysis between Malaysia and Indonesia on key indicators

Indicator	**Malaysia**	**Indonesia**
Initial technological basis	BIM and Industry 4.0	Industry 4.0 and CPS
Key early-stage sector	Construction and manufacturing	Manufacturing and Digital Management
Expansion	Infrastructure and smart cities	Digital Government and smart cities
A key example	Infrastructure projects	Nusantara
An institutional approach	Phased standardization and policies	Project-based and transformational development
Main function	Asset Management and Lifecycle Management	Urban Systems Management
Current trend	Integrated Infrastructure Digital Twins	Urban Digital Twin / Smart City
Main economic effect	Productivity and lifecycle efficiency	Resource efficiency and quality of public services

Author's construction based on a specific database.

Based on the above, a comparative analysis can be made of the development models in the two Islamic countries:

a. The Malaysian model

Malaysia demonstrates a clearer pattern of gradual institutional development:

BIM → Industry 4.0 → Digital Construction → Digital Twin → National Digital Twin

Technology is gradually being integrated into existing policies, standards and infrastructure projects. The establishment of a specialised technical committee for IoT and Digital Twins within the Department of Standards of Malaysia is an indicator of the institutionalisation and standardisation of the field.

b. The Indonesian model

Indonesia demonstrates a more project-oriented and experimental model:

Industry 4.0 → Research/Prototypes → Digital Government → Nusantara

Here, the Digital Twin is developing simultaneously as a technological platform, a tool for digital governance and a foundation for building a new smart-city ecosystem. In the case of Nusantara, it has the potential to be

integrated as early as the city's design and construction phase, which represents a significant difference from the gradual digitalisation of existing infrastructure.

VIII. DEVELOPMENT OF THE CONCEPT OF DIGITAL TWINS IN BULGARIA

The development of the concept of Digital Twins in Bulgaria should be seen as part of the broader process of digital transformation of industry, construction, urban environment and public administration. Unlike countries where the concept was initially developed predominantly within the framework of the production and management of industrial assets, in Bulgaria there is a parallel development of industrial, building and urban digital twins.

1. Initial scientific and engineering stage

The first more clearly formulated publications in the Bulgarian scientific context consider Digital Twins in relation to virtual prototyping, IoT and digital representation of physical products. Todorov, Kamberov and Zlatev examine the advantages of the concept and propose a methodological approach for its implementation, emphasizing the interaction between the physical product and its virtual analogue (Todorov, Kamberov and Zlatev, 2019, pp. 29-34). This approach shows that the initial introduction of the concept in Bulgaria is closely related to the already existing engineering technologies - CAD/CAE, virtual prototyping, automation and IoT. In this sense, the following technological sequence can be identified:

CAD/CAE → Virtual Prototype → IoT → Digital Twin

Digital Twin is gradually distinguished from the traditional digital model by the presence of a connection between the physical object and its digital representation.

2. Development of BIM and its connection with Digital Twin

The second important direction of development is related to construction and Building Information Modelling (BIM). In this context, Digital Twins can be considered as the next stage in the development of the digital representation of buildings and infrastructure objects. However, it is essential to make a conceptual distinction between BIM and Digital Twins. BIM is an information-structured digital representation of a given construction object, while a Digital Twin implies a higher degree of connectivity between the digital model and the physical object, including the use of current

data, monitoring, analysis and forecasting. This distinction is formalized in the European Technical Framework for Digital Twins in the Built Environment (CEN, 2024). In this way, the development can be represented:

BIM → IoT → Real-time Data → Simulation → Digital Twin

This transformation is particularly important, as it turns the digital model from a descriptive tool into a dynamic system for analyzing and managing a physical asset.

3. Emergence of the City Digital Twin in Bulgaria

A significant qualitative transition occurs with the development of the concept of the City Digital Twin. Of particular importance is the scientific work of Hristov, Petrova-Antonova, Ilieva and Rizov, who develop an approach to creating a City Digital Twin through Urban Living Labs (Hristov et al., 2022, pp. 151-156). The authors consider the digital twin not as a model of a separate object, but as an integrated digital environment for representing and analyzing an urban system. The study examined a pilot case in the Lozenets district of Sofia, where different types of spatial and sensor data are integrated (Hristov et al., 2022, pp. 152-154). The data used includes information on the environment, air quality, noise pollution, human mobility and other characteristics of the urban environment. They create a basis for an integrated digital representation of the territory (Hristov et al., 2022, pp. 153-55). Therefore, in the Bulgarian context, a transition is observed:

Digital Twin of an Asset → Digital Twin of an Urban System

This represents a significant conceptual expansion of the field of application.

4. GATE City Digital Twin

The GATE Institute at Sofia University "St. Kliment Ohridski" is of particular importance for the development of the Bulgarian concept. The institute is developing a pilot City Digital Twin aimed at collecting, integrating and analyzing spatial, sensor and other urban data. The main goal is to create a digital environment in which various processes in the urban system can be modeled and simulated (GATE Institute, 2024). In this model, the Digital Twin is considered as a multi-layered digital representation of the urban environment, which can be used to analyze transport, air quality, urban climate, energy efficiency and other characteristics of the urban system (GATE Institute, 2024). In the application area "Cities of the Future", GATE Institute focuses on the creation of the "digital twin" of the

city and data space as complementary technologies and models for innovation. They support intelligent data sharing, simulations and data-driven solutions in a wide range of aspects of the city - air quality, urban planning, energy efficiency, transport and logistics, mobility, etc.

The digital twin of the city is implemented as a pilot project of GATE Institute, covering the territory of Sofia with the support of Sofia Municipality. It is a copy of the physical city, which includes the collection, integration and modeling of data from the urban environment, simulation and analysis of urban processes and phenomena, and visualization of the obtained results in a way understandable for a wide range of stakeholders. The main goal of the digital twin is to provide a tool for interaction, design, experimentation and optimization of the city, which will support intelligent data-driven decision-making by Sofia Municipality.[1]

In this way, the function of the technology is transformed from Data Collection to:

Data → Model → Simulation → Scenario → Decision

This transformation is particularly important from the perspective of public governance, as the Digital Twin provides an opportunity to experiment with scenarios before taking real investment or management actions (GATE Institute, 2024).

5. Digital Twin and public administration

The development of the City Digital Twin in Bulgaria creates prerequisites for the use of technology as a tool for data-driven decision-making. In this model, the digital twin is not just an information base, but an analytical infrastructure for evaluating alternative scenarios.

For example, different options for transport, energy or spatial policy can be modeled and compared through the digital environment:

Scenario A vs. Scenario B, assessing the consequences on infrastructure, resources, the environment and urban mobility. From here arises an important economic characteristic of the Digital Twin:

Digital Twin → Ex Ante Analysis → Risk Reduction → Better Investment Decision

This allows the concept to be considered not only as a technological tool, but also as a mechanism for increasing the effectiveness of public investments.

[1] City Twin Concept. Available from: https://www.sofia.bg/city-digital-twin [Accessed September 12, 2026]

6. Digital Twin and energy efficiency

In parallel with urban applications, a direction related to smart buildings and energy efficiency is developing in Bulgaria. Within the framework of the European project Meta Cities Excellence Hub in South-Eastern Europe, Bulgaria is involved in activities related to smart buildings and energy efficiency, including the use of digital technologies to optimize energy consumption and renovation planning (European Commission, 2024). This creates an opportunity to form the following economic dependence:

Digital Twin → Energy Monitoring → Simulation → Optimization → Energy Savings

In this case, the financial value of the Digital Twin can be measured through saved energy costs, optimized investments and reduced costs over the lifecycle of the building.

7. Digital Twin and Industry 4.0

Another significant direction is the application of digital twins in smart manufacturing. Bulgarian initiatives within the framework of Erasmus+ are aimed at developing knowledge and skills for using Digital Twins as part of Industry 4.0 and smart manufacturing (Regional Chamber of Commerce and Industry - Stara Zagora, 2023). In this context, the Digital Twin is used for the virtual testing of production processes, equipment optimization, simulation before physical implementation and improvement of maintenance (Regional Chamber of Commerce and Industry - Stara Zagora, 2023). The economic mechanism can be represented as:

Digital Twin → Process Optimization → Downtime Reduction → Productivity → Financial Value

This shows that in the industrial context, Digital Twins can generate value both by increasing revenues and by reducing operating costs.

8. Institutional development

In the last stage, the Digital Twin is gradually entering the institutional discourse. Bulgarian public institutions are increasingly using concepts such as GIS, BIM, digital models, smart cities and digital twins in the context of urban infrastructure management and spatial development. However, an important methodological distinction should be made here. GIS should not automatically be defined as a Digital Twin. GIS is an infrastructure for collecting, managing, analyzing, and visualizing spatial data, while a Digital Twin requires additional dynamic connection to the physical

object, data updating, modeling, and, in its more mature form, simulation and prediction.

Therefore *GIS ≠ Digital Twin*, but GIS + *BIM* + *IoT* + *Real-time Data* + *Simulation* → *Digital Twin*

In conclusion, the following conclusions can be reached:

Firstly, the concept of Digital Twins in Bulgaria is moving from engineering-oriented digital modeling to integrated cyber-physical and urban digital systems. The most significant qualitative change is the transition from digital representation of a single asset to modeling of complex systems and processes, using real-time data, simulations and analytical models.

Secondly, the Bulgarian model has the potential to connect the technological concept of Digital Twin with the economic assessment of investments. In industrial applications, this can be measured through productivity, costs and maintenance; in buildings - through energy efficiency and lifecycle costs; and in urban Digital Twins - through the effectiveness of public investments, risk management and quality of public services.

IX. DISCUSSION

1. Conceptual heterogeneity of the digital twin

The results of the comparative analysis show that the digital twin should be considered not as an isolated technological innovation, but as an integrative concept located at the intersection of artificial intelligence, the Internet of Things (IoT), cyber-physical systems, cloud technologies, big data analytics and simulation modeling. This feature is essential for interpreting the differences between the USA, China, Bulgaria, Malaysia and Indonesia.

The existing scientific literature demonstrates significant conceptual fragmentation. Jones et al. (2020), for instance, identify multiple characteristics of the digital twin, including physical and virtual object, state, metrology, synchronization and bidirectional connection between the physical and virtual environment. Concurrently, more recent research shows that the lack of a unified definition continues to hinder comparison between individual applications and architectures (Wooley, 2026; Sharma et al., 2022).

In this context, the differences between the countries under consideration should not be interpreted solely as differences in the level of

technological development. They may reflect different conceptual interpretations of the function of the digital twin itself. While in one context it may be oriented primarily towards monitoring and optimization, in another it may be seen as an infrastructure for forecasting, autonomous control and integration of complex cyber-physical systems.

Therefore, this study supports the thesis that a distinction is needed between a universal technological core of the digital twin and a contextually determined national interpretation.

2. The digital twin as a driver, not just a result of technological transformation

One of the main questions arising from the comparative analysis is whether the digital twin is a driver of technological transformation, or rather a result of an already achieved level of digital maturity. At first glance, the implementation of digital twins presupposes the presence of a pre-built digital infrastructure - sensor networks, IoT, data management systems, computing resources, analytical platforms and AI. From this perspective, the digital twin can be interpreted to be a consequence of technological transformation. On the other hand, once implemented, it creates new opportunities for prediction, optimization and automation and thus begins to act as an accelerator of the next stage of transformation.

This allows us to propose a cyclical causal relationship:

digital maturity → digital twin → analytical and predictive capability → optimization → higher digital maturity

Therefore, the digital twin can be seen as both a result and a driver of digital transformation. Such an interpretation is consistent with the literature, which defines digital twins as systems capable of not only representing the current state of a physical object, but also supporting prediction, optimization, and management (Yao et al., 2023).

3. National context as a determinant

A comparison between the United States, China, Malaysia, Indonesia and Bulgaria, shows that the same technological concept can acquire a different strategic function depending on the national environment.

This dependence can be explained by five interrelated dimensions:

- ✓ technological infrastructure;
- ✓ institutional environment;
- ✓ national innovation policy;
- ✓ human capital;
- ✓ economic structure.

From this perspective, comparative analysis should not be reduced to a linear ranking of countries from "more developed" to "less developed". Such an approach would be methodologically limited, as it would assume the existence of a single trajectory of technological transformation.

It is more adequate to adopt a model of contextual technological transformation, in which different countries can achieve different forms of digital maturity through different institutional mechanisms.

This is particularly important for Bulgaria. Its position should not automatically be interpreted as "lagging behind" the United States or China. It is more appropriate to consider Bulgaria within the European regulatory and innovation ecosystem and as an example of an economy where European policies, national technological capacity and business capabilities intersect.

4. The United States and China: Two Different Models of Technological Transformation

The comparison between the United States and China allows us to explore the fundamental question of the role of the state and the market in the development of digital twins.

In a conditional analytical plan, two ideal types can be distinguished:

a. market-innovation model - in which the private sector, technology companies, universities and venture capital are the main drivers of technological development; and

b. strategically coordinated model - in which state policies, industrial strategies and public investments play a significant role in technological diffusion.

This distinction should not be understood as absolute. Both models involve interaction between the state, business and scientific organizations. The difference lies rather in the structure of coordination and the mechanisms for mobilizing resources. Therefore, the comparison between the United States and China can contribute to the broader debate on whether digital transformation is primarily a market process of technological diffusion or a strategic process of national technological development.

5. Bulgaria, Malaysia and Indonesia: the problem of technological catch-up

The comparative position of Bulgaria, Malaysia and Indonesia is particularly significant, as these cases allow us to examine whether digital twins can function as a tool for technological leapfrogging. The traditional model of technological development assumes a gradual accumulation of infrastructure and competencies. However, digital technologies create the opportunity to partially skip certain stages by using ready-made cloud

services, AI platforms, IoT infrastructure and international technological ecosystems. However, this opportunity should not be overestimated. The digital twin requires quality data, interoperability, qualified personnel and institutional capacity. The literature identifies standardization, resource constraints, data quality and system integration as recurring problems in the implementation of digital twins (Wooley, 2026). Therefore, the digital twin can be a tool for technologically closing the developmental gap, but only after a minimum threshold of digital and institutional readiness has been achieved.

Final Discussion

The comparative analysis of the United States, China, Bulgaria, Malaysia and Indonesia shows that the development of digital twins should be considered within the framework of a broader transformation of technological, economic and institutional systems. Although the basic technological architecture has universal characteristics, the way in which digital twins are developed, implemented and used is highly dependent on the national context.

Therefore, a comparative study does not confirm the idea of a single linear development trajectory, in which all countries go through the same stages. Rather, different trajectories are observed, determined by the combination of technological capacity, economic structure, institutional environment and national priorities.

This conclusion allows us to propose the concept of "context-dependent digital twin transformation". Within this concept, the digital twin has a common technological core, but its economic, organizational and societal value is shaped by the specific environment in which it is implemented.

From this perspective, future research should disregard the question "What is a digital twin?" to the more complex question "Under what technological, institutional, and socio-economic conditions does a digital twin become an effective driver of transformation?" It is this transition from a technological description to an explanatory model of transformation that may represent the main scientific contribution of the study.

X. CONCLUSION & RECOMMENDATION

The conducted comparative analysis of the conceptual frameworks for the development and application of digital twins in the United States, China, Bulgaria, Malaysia and Indonesia allows to formulate several general conclusions regarding the role of this technology as a tool and potential driver of technological transformation. The results obtained show that the

Digital Twin should be considered not as an isolated technological solution, but as an integrative digital paradigm that unites physical objects, processes and systems with their dynamic virtual representations through continuous exchange, processing and analysis of data.

Conceptual Conclusions

The first main conclusion of the study is that the concept of digital twins demonstrates a high degree of technological and functional convergence, despite the differences in national models of its development. In the countries studied, the digital twin gradually evolved from a modeling and simulation tool to a complex cyber-physical system capable of providing real-time monitoring, predictive analysis, simulation modeling, optimization and support for management decisions.

The second important conclusion is that the effectiveness of digital twins is directly determined by the degree of integration with other key digital technologies. The Internet of Things, artificial intelligence, machine learning, cloud computing, edge computing, high-speed communication networks and analytical platforms should not be considered as peripheral components, but as complementary elements of a comprehensive technological ecosystem. Therefore, the scientifically significant question is gradually shifting from "What is a digital twin?" to "How does a digital twin function as an integrated platform for creating information, knowledge and management value?" It is this change in perspective that is of particular importance for future research.

Comparative conclusions on national models

Comparative analysis establishes the presence of distinguishable national development trajectories, determined by the institutional structure, technological maturity, economic priorities, investment capacity and national policies in the field of digital transformation.

In the United States, the development of digital twins is largely driven by innovation and market mechanisms, with industrial enterprises, technology companies, research organizations, and private investment playing a leading role. **This model is characterized by a high degree of experimentalism, sector specialization, and an orientation towards creating economic added value.**

The Chinese model demonstrates a higher degree of strategic and institutional coordination, where digital twins fit into broader national programs for smart manufacturing, digital infrastructure, smart cities and industrial modernization. **This approach emphasizes the importance of the state as a catalyst for technological transformation and as a factor for scaling digital solutions.**

Malaysia and Indonesia represent particularly significant cases from the perspective of developing and rapidly digitizing economies. Their experience shows that digital twins can be used as a mechanism for technological catch-up, through which to accelerate the modernization of industrial, infrastructure and urban systems. At the same time, limitations related to digital infrastructure, human capital, investment resources and institutional capacity can significantly limit the scale and sustainability of implementation. In this comparative context, Bulgaria occupies a specific position. There are prerequisites for the development of digital twin applications, but there is a lack of a sufficiently high degree of systemic integration between technological, institutional, scientific and economic factors. Therefore, the main challenge facing Bulgaria is not only the acquisition of technological solutions, but the creation of a favorable national ecosystem for their sustainable implementation.

Strategic Recommendations for Bulgaria

Based on comparative analysis, the following strategic recommendations can be made:

Firstly, it is necessary to include digital twins more clearly in national and sectoral policies for digital transformation. They should be positioned in the context of the broader ecosystem of Industry 4.0/5.0, artificial intelligence, smart infrastructure and the data economy.

Secondly, it is advisable to develop a national conceptual and methodological framework for digital twins, which would define the main principles, architectural requirements, standards, interoperability criteria and indicators for assessing effectiveness.

Thirdly, the construction of pilot and demonstration digital twins in strategic sectors for Bulgaria should be stimulated. The “proof of concept first, then scale up” approach would allow limiting investment risk and accumulating national expertise.

Fourthly, it is necessary to create a closer institutional connection between universities, research organizations, technology companies and the public sector. This would allow the formation of national science and innovation ecosystems oriented towards the development of applicable solutions.

Fifthly, human capital development policies must be adapted to the interdisciplinary nature of technology. A transition is needed from training focused on individual technological competencies to the formation of experts capable of integrating engineering, information, analytical and management knowledge.

Sixthly, cybersecurity, data protection and the contextual reliability of AI-based analytical models must be an integral part of the architecture of digital twins, and not an afterthought.

Research Perspectives

This study also outlines several directions for future research. It is necessary to develop unified indicators for measuring the maturity and economic efficiency of digital twins, which would allow for more precise inter-state and inter-sectoral comparison.

Another promising direction is the study of the relationship between digital twins and generative artificial intelligence, autonomous systems and spatial digital environments. Of particular importance is the question of the extent to which future digital twins will be able not only to predict states, but also to autonomously generate, evaluate and recommend optimal management actions.

Moreover, it is also necessary to deepen research on the social, ethical and regulatory dimensions of the technology, including issues of transparency of algorithmic decisions, responsibility in automated management and data ownership.

Summary of the research conclusion

In summary, the results of the comparative analysis confirm the thesis that digital twins are not just a technological innovation, but a structural component of the emerging architecture of digital transformation. Their strategic significance stems from their ability to integrate data, models, artificial intelligence and physical systems into a unified environment for monitoring, forecasting, simulation and lifecycle management.

At the same time, the comparison between the United States, China, Bulgaria, Malaysia and Indonesia shows that there is no universal implementation model. The effectiveness of digital twins is the result of the interaction between technological maturity, institutional capacity, investment environment, human capital, regulatory framework and national strategic priorities.

References:

1. Construction Industry Development Board Malaysia (CIDB) (2025) Digital Twin Technology in Malaysia's Construction Industry. Kuala Lumpur: CIDB Malaysia, 20-25.
2. Construction Industry Development Board Malaysia (CIDB) (2020) "BIM - Digitising Construction Beyond 2020", Construction from a New Angle, Issue 3, August-December 2020, pp. 14-17. Kuala Lumpur: CIDB Malaysia.

3. Ministry of International Trade and Industry (MITI) (2018) Industry4WRD: National Policy on Industry 4.0. Kuala Lumpur: Ministry of International Trade and Industry Malaysia, pp. 5-7, 14-18.
4. CEN (2024) CEN/TR 18077:2024 – Building Information Modelling - Digital Twins Applied to the Built Environment - Use Cases. Brussels: European Committee for Standardization, pp. 1-35.
5. European Commission (2024) MetaCities Excellence Hub in South-Eastern Europe. Brussels: European Commission.
6. Gaffinet, B., Al Haj Ali, J., Naudet, Y. and Panetto, H. (2025) Human Digital Twins: A systematic literature review and concept disambiguation for Industry 5.0, Computers in Industry, 166, 104230.
7. GATE Institute (2024) GATE City Digital Twin Pilot Project. Sofia: GATE Institute, Sofia University "St. Kliment Ohridski".
8. Glaessgen, E.H. and Stargel, D.S. (2012) The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, pp. 1-14. DOI: 10.2514/6.2012-1818.
9. Husni, H.S., Gaol, F.L., Supangkat, S.H. and Ranti, B. (2022) Digital Twin Concept for Indonesia Digital Government Information Technology Governance, International Journal Science and Technology, 1(2), pp. 45-52. DOI: 10.56127/ijst.v1i2.146.
10. Hristov, P.O., Petrova-Antonova, D., Ilieva, S. and Rizov, R. (2022) Enabling City Digital Twins through Urban Living Labs, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLIII-B1-2022, pp. 151-156. doi: 10.5194/isprs-archives-XLIII-B1-2022-151-2022.
11. Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020) Characterising the Digital Twin: A systematic literature review, CIRP Journal of Manufacturing Science and Technology, 29, pp. 36-52.
12. National Administration for Market Regulation (2024) GB/T 45109.1-2024: Smart City-City Digital Twin-Part 1: Technical Reference Architecture. Beijing: State Administration for Market Regulation and Standardization Administration of China. Published 31 December 2024; effective 1 July 2025.
13. National Administration for Market Regulation (2025a) GB/T 45616.2-2025: Automation Systems and Integration-Digital Twin Framework for Manufacturing-Part 2: Reference Architecture. Beijing: State Administration for Market Regulation and Standardization Administration of China. Effective 1 March 2026.
14. National Administration for Market Regulation (2025b) GB/T 45873-2025: Information Technology-Digital Twin for Workshop-Reference Architecture. Beijing: State Administration for Market Regulation and Standardization Administration of China. Effective 1 January 2026.

15. Rachmawati, R., Rohmah, A.A., Reinhart, H., Sensuse, D.I. and Sunindyo, W.D. (2024) Metaverse, Digital Twins, and Smart Sustainable Urban Development Concepts for Nusantara Capital City, Indonesia, International Journal of Sustainable Development and Planning, 19(12), pp. 4613-4621. DOI: 10.18280/ijsdp.191210.
16. Regional Chamber of Commerce and Industry - Stara Zagora (2023) Digital Twin on Smart Manufacturing. Stara Zagora: Regional Chamber of Commerce and Industry.
17. Shao, G. and Helu, M. (2020) 'Framework for a Digital Twin in Manufacturing: Scope and Requirements', Manufacturing Letters, 24, pp. 105-107. DOI: 10.1016/j.mfglet.2020.04.004.
18. Shao, G. (2021) Use Case Scenarios for Digital Twin Implementation Based on ISO 23247. NIST Advanced Manufacturing Series 400-2. Gaithersburg, MD: National Institute of Standards and Technology. DOI: 10.6028/NIST.AMS.400-2.
19. Shao, G., Frechette, S.P. and Srinivasan, V. (2023) An Analysis of the New ISO 23247 Series of Standards on Digital Twin Framework for Manufacturing. Gaithersburg, MD: National Institute of Standards and Technology.
20. Shao, G., Kibira, D. and Frechette, S.P. (2024) Digital Twins for Advanced Manufacturing: The Standardized Approach, in Digital Twins, Simulation, and Metaverse. Cham: Springer Nature.
21. Shao, G. (2024) Manufacturing Digital Twin Standards, 2024 International Conference on Engineering Digital Twins (EDTconf 2024), Linz, Austria.
22. Sharma, A., Kosasih, E., Zhang, J., Brintrup, A. and Calinescu, A. (2022) Digital Twins: State of the art theory and practice, challenges, and open research questions, Journal of Industrial Information Integration, 30, 100383.
23. Todorov, G., Kamberov, K. and Zlatev, B. (2019) Izsledvane predimstvata i algoritam za implementatsiyata na kontseptsiyata za digitalni bliznatsi ['Study of the Advantages and an Algorithm for the Implementation of the Digital Twin Concept'], Mashinostroene i Elektrotehnika, (4), pp. 29-34.
24. Wooley, A. (2026) Digital Twins Across Domains: A Cross-Industry Umbrella Review of Systematic Literature Reviews, Systems Engineering.
25. Wu, H., Ji, P., Ma, H. and Xing, L. (2023) A Comprehensive Review of Digital Twin from the Perspective of Total Process: Data, Models, Networks and Applications, Sensors, 23(19), 8306. DOI: 10.3390/s23198306.
26. Yao, J.-F. et al. (2023) Systematic review of digital twin technology and applications, Visual Computing for Industry, Biomedicine, and Art, 6, 10.
27. Zhang, J., Chen, C., Cui, Y., Zhang, Y., Han, P., Meng, N. and Xu, Y. (2022) Digital Twin City Framework and Development Suggestions, Information and Communications Technology and Policy, 48(12), pp. 2-11. DOI: 10.12267/j.issn.2096-5931.2022.12.001.

APPENDICES

Appendix #1

Table 13

Major Contributions of American Scholars to the Development of the Digital Twin Concept, 1991-2026

American scholar(s) / research community	Year	Principal publication / contribution	Major scholarly contribution	Significance for the development of the Digital Twin concept
David Gelernter	1991	Mirror Worlds: Or the Day Software Puts the Universe in a Shoebox	Advanced the idea of digitally representing real-world environments, processes and activities within computational systems.	Constitutes an important intellectual precursor to the Digital Twin concept, although it does not constitute a Digital Twin in the contemporary engineering sense.
Michael W. Grieves	2002	Conceptual model developed within Product Lifecycle Management (PLM)	Formulated a conceptual model linking a physical entity, its virtual representation and the information connecting the two.	Represents the fundamental conceptual foundation of the contemporary Digital Twin paradigm.
Michael W. Grieves	2005-2006	Mirrored Spaces Model / Information Mirroring Model	Further developed the relationship between physical and virtual spaces and formalized the information exchange between them.	Established the conceptual basis for the later Physical Entity-Virtual Entity-Data Connection architecture.
Michael W. Grieves and John Vickers	2010-2011	Development of the Digital Twin concept	Extended the original PLM concept towards a comprehensive digital representation associated with a physical system throughout its lifecycle.	Strengthened the interpretation of the Digital Twin as a dynamic cyber–physical and lifecycle-oriented information system.
John Vickers / NASA	2010	NASA technological road mapping activities	Contributed to the institutionalization and consolidation of the term Digital Twin within NASA's technological development programmers.	Constituted an important transition from a conceptual model to an institutionally recognized technological paradigm.
Edward H. Glaessgen and David S. Stargel	2012	The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles	Defined the Digital Twin as an integrated, multi-physics, multi-scale and probabilistic simulation incorporating physical models, sensor data, historical information and	Provided one of the most influential engineering formulations of the Digital Twin paradigm.

			fleet-level knowledge.	
Shafto, Conroy, Doyle, Glaessgen, Kemp, LeMoigne and Wang	2012	NASA technical formulation of the Digital Twin	Developed a formal technical framework integrating high-fidelity simulation, observational data and lifecycle information.	Expanded Digital Twin towards prognostics, diagnostics, reliability assessment and lifecycle management.
Glaessgen and Stargel / NASA-U.S. Air Force research community	2012 onwards	Lifecycle-oriented Digital Twin paradigm	Connected Digital Twin technology with integrated vehicle health management, maintenance history and fleet-level operational data.	Established the foundations for predictive maintenance, condition-based maintenance and lifecycle optimization.
Shao and Helu / NIST	2020	Framework for a Digital Twin in Manufacturing: Scope and Requirements	Synthesized competing interpretations of Digital Twin and identified its principal characteristics and implementation requirements for manufacturing use cases.	Shifted the discussion towards a fit-for-purpose and standardized manufacturing framework, thereby facilitating practical implementation.
Shao / NIST	2021	Use Case Scenarios for Digital Twin Implementation Based on ISO 23247	Developed practical implementation scenarios for manufacturing Digital Twins based on the emerging ISO 23247 framework.	Connected conceptual development with standardized manufacturing use cases.
NIST and international standards community	2021	ISO 23247 – Digital Twin Framework for Manufacturing	Established an international reference framework for Digital Twins in manufacturing.	Represented a major step towards standardization, interoperability and scalability of Digital Twin systems.
Kibira and Weiss / NIST	2022	Towards a Digital Twin of a Robot Work cell to Support Prognostics and Health Management	Applied Digital Twin principles to robotic work cells and integrated them with prognostics and health management.	Extended Digital Twin towards predictive maintenance, fault diagnosis and risk management.
Lin, Watson, Shao, Stojanovic and Zarkout	2023	Digital Twin Core Conceptual Models and Services	Developed core conceptual models and services addressing representation, diagnosis, prediction, optimization, control and interoperability.	Advanced the architectural and functional formalization of Digital Twin systems and established a basis for interoperable implementations.
Shao, Hightower and Schindel	2023	Credibility Consideration for Digital Twins in Manufacturing	Examined the credibility of Digital Twin outputs as a basis for engineering and managerial decision-making.	Introduced credibility and evidential reliability as important conditions for the operational and economic use of Digital Twins.

Akcay et al.	2023	Maintenance and Operations of Manufacturing Digital Twins	Addressed the lifecycle of the Digital Twin itself, from requirements definition and development through operation and eventual decommissioning.	Extended lifecycle thinking from the physical asset to the Digital Twin as an information system.
Shao / NIST	2024	Manufacturing Digital Twin Standards	Analyzed standards, implementation challenges, use cases and future directions for Digital Twin standardization.	Reinforced standardization as a prerequisite for interoperability, reusability and scalable implementation.
Shao, Kibira and Frechette / NIST	2024	Digital Twins for Advanced Manufacturing: The Standardised Approach	Developed a standards-oriented approach to Digital Twins for advanced manufacturing	Supported the transition from isolated implementations towards a coherent and interoperable Digital Twin ecosystem.
David et al.	2024	Interoperability of Digital Twins: Challenges, Success Factors, and Future Research Directions	Examined interoperability between connected, aggregated and hierarchical Digital Twins.	Extended the concept from a single Digital Twin towards interconnected and federated Digital Twin environments.
Voas, Mell, Laplante and Piroumian / NIST	2025	Security and Trust Considerations for Digital Twin Technology	Examined security, trust, monitoring, simulation and real-time command within Digital Twin environments.	Established security and trustworthiness as essential conditions for reliable large-scale Digital Twin deployment.
Reslan et al. / NIST	2025	Automation of Value Stream Mapping: A Case Study on Enhancing Lean Manufacturing Tools Through Digital Twins	Connected Digital Twin technology with Lean manufacturing and value-stream analysis.	Particularly relevant to the economic dimension of Digital Twin through its implications for productivity, resource efficiency and value creation.
Kibira and Shao / NIST	2026	Data Requirements for a Digital Twin of a CNC Machine Tool	Examined the data requirements necessary for the construction and effective operation of a CNC machine-tool Digital Twin.	Strengthened the focus on data quality, data requirements and data-driven validity as determinants of Digital Twin effectiveness.

Author's construction based on a specific database.

Appendix #2

Table 14

Periodization of the American contribution to Digital Twin research, 2020-2026

Period	Developmental stage	Principal research focus	Principal scholarly outcome
2020-2021	Framework development and standardization.	Manufacturing frameworks, scope, requirements, use cases, ISO 23247, cybersecurity and trust.	Transition from conceptual models towards structured and standardized Digital Twin frameworks.

2022-2023	Operationalization and predictive capability.	Prognostics and health management, predictive maintenance, human-centered Digital Twins, credibility, conceptual models and services.	Digital Twin has become an operational, predictive and decision-support system.
2024-2026	Interoperability, security, data and economic value.	Standardization, interoperability, security, trust, data requirements, Lean manufacturing and value creation	Digital Twin develops into a standardized, interoperable, trustworthy and economically actionable system

Author's construction based on a specific database.

Appendix #3

Table 15

Major Contributions of Chinese Authors and Research Communities to the Development of the Digital Twin Concept, 2019-2026

Author(s) / Research Community	Year	Principal Publication / Normative Document	Major Contribution	Academic Significance	Pages (DOI) Standard
Tao, F. et al.	2019	Digital Twin-driven Product Design Framework	Developed a conceptual framework for Digital Twin-driven product design, integrating the physical product, its virtual representation, data, and the design process.	Established an important foundation for understanding Digital Twin as an engineering and lifecycle management paradigm, rather than merely as a digital representation.	International Journal of Production Research, 57(12), pp. 3935-3953. DOI: 10.1080/00207543.2018.1443229
Zhang, J. et al.	2022	Digital Twin City Framework and Development Suggestions	Conceptualized Digital Twin City and proposed a development framework encompassing technological characteristics, development	Made a significant contribution to extending Digital Twin from the industrial domain to the urban and societal scale.	Information and Communications Technology and Policy, 48(12), pp. 2-11. DOI: 10.12267/j.issn.2096-5931.2022.12.001

			visions, and key implementation elements.		
Wu, H., Ji, P., Ma, H. and Xing, L.	2023	A Comprehensive Review of Digital Twin from the Perspective of Total Process: Data, Models, Networks and Applications	Systematized Digital Twin through four fundamental dimensions: data, models, networks, and applications.	Provided an important theoretical and methodological synthesis of Digital Twin as an integrated dynamic system.	Sensors, 23(19), 8306. DOI: 10.3390/s23198306
Yu, P., Zhao, Z. and Sampat, M.	2023	How Digital Twin Technology Promotes the Development of Smart Cities: Case Studies in China	Examined the role of government, public policy, and institutional arrangements in the development of Digital Twin-enabled smart cities in China.	Extended the analysis towards the institutional, governance, and economic dimensions of Digital Twin development.	pp. 198-227. DOI: 10.4018/978-1-6684-3833-6.ch008
Chinese national standardization community / TC28	2023	GB/T 43441.1-2023 - Information Technology - Digital Twin -Part 1: General Requirements	Established general national requirements for Digital Twin systems.	Represents a significant transition from an academic and technological concept towards a nationally standardized technological category.	GB/T 43441.1-2023
Chinese research and standardization organization's / CAICT and associated institutions	2024-2025	GB/T 45109.1-2024 - Smart City - City Digital Twin - Part 1: Technical Reference	Established a national technical reference architecture for	Represents a major step towards the architectural and institutional standardization of	GB/T 45109.1-2024; published 31 December 2024; effective July 1, 2025

		Architec-ture	City Digital Twins, cover-ing in-frastruc-ture, data re-sources, digital engines, twin ser-vices, inter-faces, security, and op-era-tional manage-ment.	Digital Twin City.	
Guo, N., Hu, L., Han, L., Jia, S. et al.	2023-2025	GB/T 43441.1-2023 – Digital Twin—Part 1: General Require-ments	Contrib-uted to the de-velop-ment of general national require-ments for Dig-ital Twin, includ-ing ter-minol-ogy, general princi-ples, and sys-tem re-quire-ments.	Contributed to the unifi-cation of terminol-ogy, re-quirements, and archi-tectural foundations for Digital Twin de-velopment in China.	GB/T 43441.1-2023
Hu, L., Han, L., Li, J., Guo, N. et al.	2025	GB/T 45626-2025 - In-formation Technol-ogy - Equipment Digital Twin Sys-tem-Gen-eral Re-quirements	Devel-oped general require-ments for Equip-ment Digital Twin Sys-tems, involv-ing aca-demic, re-search, and in-dustrial institu-tions.	Extended national standardi-zation from the general concept to-wards spe-cific tech-nical sys-tems and equipment-level Digi-tal Twins.	GB/T 45626-2025

Tao, F. and the broader Chinese standardization community	2025-2026	GB/T 45616.2-2025 - Digital Twin Framework for Manufacturing-Part 2: Reference Architecture	Formalized a reference architecture for manufacturing Digital Twins.	Strengthening the position of Digital Twin as a structural component of intelligent manufacturing and industrial digital transformation.	GB/T 45616.2-2025; effective March 1, 2026
Research communities at Beihang University and associated institutions	2025-2026	GB/T 45873-2025 - Information Technology - Digital Twin for Workshop -Reference Architecture	Developed a reference architecture for Workshop Digital Twins.	Demonstrates the vertical expansion of Digital Twin from general frameworks towards a specific manufacturing level - workshops and production units.	GB/T 45873-2025; effective January 1, 2026
Chinese national standardization community / TC28SC41	2025-2026	GB/T 46237-2025 – Information Technology-Digital Twin Capability Maturity Model	Introduced a Digital Twin capability maturity model.	Particularly important for assessing Digital Twin not only in technological terms but also in terms of organizational capability, technological maturity, and economic performance.	GB/T 46237-2025; effective May 1, 2026
Chinese national standardization community / TC28SC41	2026	GB/T 43441.2-2026 - Information Technology - Digital Twin -Part 2: Digital Entity	Further developed the national Digital Twin framework by formalizing the concept of a Digital Entity as a fundamental component	Demonstrates the transition towards a modular and formally structured national Digital Twin architecture.	GB/T 43441.2-2026; effective August 1, 2026

			of the Digital Twin archi-tecture.		

Author's construction based on a specific database.

Appendix #4

Table 16

A chronological overview of the development of the concept of digital twins in China

Period	Stage	Key characteristic
By 2015	Technological prerequisites	IoT, GIS, simulation, informatization
2015 - 2020	Industrial Digital Twin	Intelligent Manufacturing u Industrial Internet
2021 - 2022	Strategic institutionalization	Digital Twin City as a national priority
2022 - 2024	Conceptual and architectural formali-zation	Frameworks and technical reference models
2024 - 2025	National standardization	GB/T 45109.1-2024
2025 - 2026	Sectoral standardization	Manufacturing u workshop Digital Twins
Next stage	Digital Governance Ecosystem	AI + Digital Twin + Data infrastructure

Author's construction based on a specific database.

Appendix #4

Table

Periodization of the development of the concept of the digital twin in Bulgaria

Stage	Period	Characteristics	Main sources
I	2019-2020	Engineering and manufacturing applica-tions	Todorov, G., Kamberov, K. and Zlatev, B. (2019)
II	2020-2022	BIM and digital modeling	CEN (2024) CEN/TR 18077:2024)
III	2021-2024	City Digital Twin	Hristov, P.O., Petrova-An-tonova, D., Ilieva, S. and Ri-zov, R. (2022)
IV	2022-2025	Smart Buildings and Energy Twin	European Commission (2024)
V	2023-2026	Industrial Digital Twin	Regional Chamber of Com-merce and Industry - Stara Zagora (2023)
VI	2024-2026	Institutionalization and public management	GATE Institute (2024) GATE City Digital Twin Pi-lot Project.

Author's construction based on a specific database.

DIGITAL TWINS IN MARKETING AND CONSUMER ANALYTICS

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Abstract: *This paper explores how digital twin technology can improve marketing decision-making through better consumer understanding, behavioural prediction, personalisation and simulation of marketing strategies. It examines the potential benefits of digital twins alongside challenges related to data quality, accuracy, privacy and consumer trust. The article concludes that digital twins can support more informed marketing decisions when implemented responsibly and supported by reliable data.*

Keywords: *Digital twins, consumer behaviour, marketing decision-making, predictive analytics, personalisation, consumer trust*

Introduction

Digital transformation has significantly changed the way organizations understand consumers and make marketing decisions. Companies now collect large quantities of information from websites, mobile applications, loyalty programs, social media, connected devices, online transactions, and other digital touchpoints. Although access to data has expanded rapidly, having more data does not automatically result in better marketing decisions. Marketers still face the challenge of integrating fragmented information, interpreting changing consumer behavior, and predicting how individual customers or market segments may react to future marketing actions. Digital twin technology offers a potential solution to this problem by transforming consumer data into dynamic representations that can be analyzed and simulated.

A digital twin can generally be understood as a data-driven virtual representation of a real-world entity or system. The concept was initially associated primarily with manufacturing, engineering, and physical assets, where digital representations could be continuously updated with real-world data. More recently, researchers have extended the idea to people and consumers. Consumer digital twins and human digital twins use behavioral, demographic, transactional, psychological, and other forms of data to model individuals or groups and potentially predict their future

responses. These developments create important opportunities for marketing because marketers are fundamentally concerned with understanding, predicting, and influencing consumer decisions.

This paper argues that **digital twins can improve marketing decision-making by creating more integrated and dynamic representations of consumers, strengthening behavioral prediction, enabling more precise personalization, and allowing marketers to simulate decisions before implementing them in the real market**. However, digital twins should not be treated as perfect replicas of consumers. Their usefulness depends on the quality and representativeness of the underlying data, the validity of the models, and responsible management of privacy, transparency, and consumer trust.

From Traditional Consumer Analytics to Digital Twins

Traditional marketing analytics uses historical data to identify patterns in customer behavior. Customer relationship management systems, segmentation models, recommendation algorithms, surveys, and predictive analytics can help marketers determine who their customers are and what they are likely to purchase. Nevertheless, these approaches frequently provide only partial views of consumer behavior. Information may exist in separate databases, and customer profiles can quickly become outdated when consumer preferences change.

Digital twins represent a potential evolution from relatively static customer profiles toward dynamic behavioral models. Attaran and Celik (2023) describe digital twins more broadly as virtual representations supported by data and analytical technologies that can help organizations monitor systems, conduct simulations, and improve decision-making. Applying this logic to marketing means that the object being represented is no longer necessarily a machine, factory, or physical process. It may instead be an individual consumer, customer segment, shopping environment, or customer journey.

Recent research has begun to formalize this concept. Consumer digital twins can combine multiple sources of information to represent consumer characteristics and behavior and can be updated as new information becomes available. Botha et al. (2025), for example, describe human digital twins in marketing as AI-generated, data-driven consumer replicas that can help marketers analyze and predict consumer behavior. Such models can incorporate information about previous online behavior and preferences to estimate possible future choices.

The development of large-scale behavioral datasets also demonstrates how digital twins could move beyond simple demographic segmentation. Toubia et al. (2025) introduced the Twin-2K-500 dataset, containing responses from 2,058 participants to more than 500 questions across several survey waves. The dataset includes demographic, psychological, economic, personality, cognitive, and behavioral information. The researchers argue that such comprehensive individual-level data can support the construction and evaluation of digital twins capable of predicting behavior at both individual and aggregate levels.

This development is important for marketing because consumers who appear similar according to traditional demographic variables can behave very differently. Two consumers of the same age, income, and location may have different attitudes toward risk, brands, sustainability, prices, promotions, or technology. A richer digital representation can therefore potentially give marketers a more realistic basis for decision-making than a customer profile built around a small number of variables.

Improving Consumer Prediction and Marketing Decisions

One of the strongest arguments for using digital twins in marketing is their potential to improve predictions about consumer behavior. Marketing decisions are inherently forward-looking. Managers must decide which customers to target, what products to recommend, which promotional offers to provide, how to allocate advertising resources, and how customers may react to changes in price or customer experience. Historical data can inform these decisions, but digital twins potentially allow marketers to move from describing past behavior toward simulating future behavior.

This predictive capability becomes particularly important when consumer data are complex and continuously changing. A consumer digital twin could theoretically integrate transaction history, browsing activity, previous responses to promotions, product preferences, customer-service interactions, and contextual information. Instead of evaluating each variable separately, marketers could use the combined representation to estimate how the consumer might respond under different conditions.

Toubia et al. (2025) provide an important foundation for this possibility by demonstrating the development of a large-scale dataset intended specifically for digital-twin simulation of human behavior. Their research highlights both the potential of large language model-based digital twins and an important methodological requirement: digital twins require high-quality ground-truth data against which their predictions can be evaluated. Therefore, the managerial value of a digital twin does not simply come

from using sophisticated artificial intelligence. Its predictions must also be tested against actual human behavior.

Digital twins could consequently function as decision-support tools rather than replacements for marketing managers. Before launching an expensive campaign, for example, a marketer could potentially simulate how different consumer representations might react to alternative messages, offers, or customer experiences. The purpose would not be to assume that simulated responses perfectly predict reality. Instead, simulations could identify possible outcomes, reveal differences among consumer groups, and help managers choose which strategies deserve further real-world testing. This ability to conduct virtual experimentation is particularly valuable because many marketing decisions involve significant uncertainty. Traditional experiments and A/B tests remain important because they measure actual consumer responses, but they require time, exposure to real customers, and sometimes substantial financial resources. Digital-twin simulation could complement these methods by allowing marketers to evaluate a larger number of scenarios before selecting the most promising alternatives for real-world experiments.

Personalization and the Customer Journey

Digital twins can also improve marketing decisions by supporting more dynamic personalization. Modern consumers interact with organizations through combinations of physical and digital channels. A customer might discover a product through social media, research it through a mobile device, inspect it in a physical store, purchase it online, and later contact customer support. Treating each interaction separately can produce an incomplete understanding of the customer's experience.

Quach et al. (2026) investigate digital twins in the context of personalized experiences across the “phygital” customer journey, meaning journeys that combine physical and digital environments. Their research emphasizes the value of dynamic personas rather than assuming that one static customer persona can accurately represent an individual across every situation. This distinction is significant because consumer preferences are contextual. A consumer's priorities when casually browsing may differ from those present when the same person is making an urgent purchase.

Digital twins therefore offer a possible mechanism for adapting personalization as the customer journey develops. Rather than assigning a consumer permanently to a broad segment, a digital-twin system could theoretically update the representation as new interactions occur. Marketing

decisions concerning recommendations, communication channels, timing, and offers could then reflect more recent behavior.

Retail research provides a practical example of the strategic implications. Yang et al. (2026) examine retailer-owned digital-twin services and their relationship with customer experience, product misfit returns, and investment costs. Their findings demonstrate that the value of digital twins is not limited to promotional communication. Digital-twin decisions can influence broader retail outcomes, including customer experience, returns, pricing, manufacturer relationships, and profitability. The study also shows that adoption is not automatically beneficial in every situation; costs and market conditions influence whether the technology creates value.

Consequently, digital twins can improve marketing decisions when they connect customer analytics with broader business outcomes. A highly personalized recommendation has limited value if it increases operational costs, damages consumer trust, or creates an unprofitable transaction. Effective marketing decisions must therefore evaluate customer-level predictions alongside organizational and financial consequences.

Consumer Acceptance, Privacy, and Trust

Despite their potential benefits, consumer digital twins create substantial ethical and managerial challenges. A technology designed to predict an individual's future choices requires extensive personal information. The more detailed the digital representation becomes, the more important questions of consent, privacy, transparency, security, and consumer autonomy become.

Botha et al. (2025) directly investigated consumer acceptance of marketers' use of human digital twins. Their study of South African consumers examined perceived usefulness, perceived ease of use, knowledge, trust, and technological proficiency. All five factors were found to have statistically significant positive relationships with consumer acceptance. These results indicate that technological capability alone does not determine whether digital twins will succeed in marketing. Consumers must also understand, trust, and perceive value in the technology.

Privacy concerns can also influence the economic attractiveness of digital twins. Yang et al. (2026) found a more complex relationship between privacy concerns and retailers' incentives to adopt digital-twin services. This suggests that marketers cannot simply assume that collecting more personal data always produces more value. A system that improves predictive accuracy but creates strong consumer resistance may ultimately damage customer relationships.

Privacy-preserving architectures may partially address these concerns. Rachamim and Hornik (2026) propose a federated digital-twin framework for consumer wellbeing systems that integrates decentralized and multimodal information while emphasizing privacy and autonomy. Federated approaches are important because they suggest that the development of sophisticated consumer models does not necessarily require every piece of personal information to be centralized in one database.

Responsible implementation should therefore be treated as part of marketing effectiveness rather than as a separate compliance problem. Trust is itself an important component of customer relationships. If consumers believe that companies are creating hidden replicas of them to manipulate purchasing decisions, the technology could undermine the customer experience it is intended to improve. Organizations should consequently establish transparent policies concerning what information is collected, why it is used, how long it is retained, and how automated predictions affect marketing decisions.

Limitations of Digital Twins in Consumer Analytics

One of the main limitations of digital twins is the risk of treating a digital representation as an accurate reflection of the actual consumer. Digital twins are models, and like any model, they simplify reality. Consumer behaviour is shaped by emotions, social relationships, unexpected events, cultural context, economic circumstances and changing preferences. Even highly sophisticated systems cannot fully capture all the factors that influence a consumer's purchasing decisions.

Data quality creates an additional problem. If a digital twin is trained using incomplete, outdated, or biased data, its predictions may reproduce those limitations. Consumers with extensive digital histories may be represented more accurately than consumers with limited recorded activity. This could create unequal personalization or systematically weaker decisions for particular groups.

Toubia et al. (2025) indirectly highlight this problem by emphasizing the importance of large, detailed, individual-level datasets and test-retest benchmarks for evaluating digital twins. Reliable validation is therefore essential. Marketers should compare simulated predictions with observed consumer outcomes and continuously evaluate whether accuracy deteriorates as market conditions and consumer behavior change. There is also a danger that increasingly sophisticated consumer models could encourage excessive confidence in automated decision-making. Marketing managers should not assume that an AI-generated consumer twin “knows” what an

individual will do. Digital twins are more appropriately interpreted as probabilistic decision-support systems. They can indicate patterns and possible responses, but uncertainty should remain visible in managerial decisions.

For this reason, digital twins are likely to provide the greatest value when combined with existing marketing research rather than replacing it. Surveys, interviews, ethnographic research, experiments, customer feedback, transactional analytics, and managerial judgment can provide evidence that digital-twin simulations cannot independently capture. The strongest marketing analytics system would therefore combine simulated consumer behavior with evidence from actual consumers.

Conclusion

Digital twins represent an important emerging development in marketing and consumer analytics because they can transform fragmented consumer data into more integrated, dynamic, and potentially predictive representations. The technology can improve marketing decision-making in several ways. Digital twins can provide richer models of consumers than traditional static profiles, support predictions of future behavior, enable simulations of alternative marketing strategies, facilitate personalization across physical and digital customer journeys, and connect customer-level decisions with broader retail outcomes.

The emerging research therefore supports the central argument that digital twins can improve marketing decisions. However, improvement is conditional rather than automatic. The effectiveness of consumer digital twins depends on high-quality data, appropriate model validation, organizational capabilities, and continuous comparison between simulations and actual behavior. Moreover, consumer acceptance, privacy, transparency, and trust can determine whether technically effective digital-twin systems produce sustainable marketing value. Digital twins should consequently be understood not as perfect virtual copies of consumers but as advanced analytical models for decision support. Their greatest contribution to marketing may be their ability to allow managers to ask more sophisticated “what if” questions before acting in the real marketplace. Used responsibly and combined with traditional consumer research, digital twins could reduce uncertainty and enable more evidence-based marketing decisions. Used without adequate validation or ethical safeguards, however, they could create inaccurate predictions and damage consumer trust. The future value of digital twins in marketing will therefore depend as much on responsible implementation as on advances in artificial intelligence.

References:

1. Attaran, M., & Celik, B. G. (2023). Digital twin: Benefits, use cases, challenges, and opportunities. Decision Analytics Journal, 6, Article 100165.
2. Botha, M., Cullen, M., & Calitz, A. P. (2025). Factors influencing South African consumer acceptance of marketers' use of human digital twins (HDTs). The African Journal of Information and Communication, 36, 1–13.
3. Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. IEEE Access, 8, 108952–108971.
4. Hornik, J., & Rachamim, M. (2026). AI-enabled consumer digital twins as a platform for research aimed at enhancing customer experience. Management Review Quarterly, 76, 2231–2264.
5. Lemon, K. N., & Verhoef, P. C. (2016). Understanding customer experience throughout the customer journey. Journal of Marketing, 80(6), 69–96.
6. Quach, K., Nguyen, T. T., Quach, S., Pham, H. T., Weaven, S., Nguyen, Q. V. H., Nguyen, T. T., & Thaichon, P. (2026). Digital twins: Enhancing personalized experience through multiple and dynamic persona across customer phygital journey. Australasian Marketing Journal, 34(1), 86–102.
7. Rachamim, M., & Hornik, J. (2026). A federated digital twin framework for consumer wellbeing systems. Systems, 14(4), Article 417.
8. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415.
9. Toubia, O., Gui, G. Z., Peng, T., Merlau, D. J., Li, A., & Chen, H. (2025). Database report: Twin-2K-500: A data set for building digital twins of over 2,000 people based on their answers to over 500 questions. Marketing Science, 44(6), 1446–1455.
10. Wedel, M., & Kannan, P. K. (2016). Marketing analytics for data-rich environments. Journal of Marketing, 80(6), 97–121.
11. Yang, Q., Sun, L., Wu, X., & Li, Y. (2026). Implications of retailer-owned digital twins services: The trade-offs between customer experience, misfit returns reduction, and investment costs. Journal of Retailing and Consumer Services, 88, Article 104478.

BURGAS FREE UNIVERSITY AI VOICE ASSISTANT

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Abstract: *This article discusses the development and implementation of a voice assistant with artificial intelligence (AI), designed for integration into the information infrastructure of Burgas Free University. The presented software solution combines modern technologies for local speech recognition (Speech-to-Text), cloud generation of contextual responses through large language models (LLMs) and voice synthesis (Text-to-Speech) in Bulgarian. A detailed description of the system architecture is made, two cross-platform implementations (WinUI 3 for Windows and Python for Linux/Raspberry Pi) are presented, and the experimental results, limitations and guidelines for future development of the project are analyzed.*

Keywords: *Artificial Intelligence, Voice Assistant, Large Language Models (LLM), Speech-to-Text, Text-to-Speech, Bulgarian*

1. Introduction

With the rapid development of generative artificial intelligence and natural language processing (NLP), new horizons are opening up for building more natural and intuitive user interfaces. Traditional text interfaces and menus are gradually being complemented or replaced by voice technologies that facilitate access to information and improve the user experience. In the context of higher education and in particular for the needs of Burgas Free University, the implementation of a specialized voice assistant can optimize administrative and training processes through:

- Providing quick voice access to schedules, curricula, and university information.
- Automation of the first level of technical and administrative support for students and prospective students.
- Providing an interactive learning environment, counselling and support for visually disadvantaged students (e.g. visually impaired).

The main challenge in the implementation of such a system is to ensure high quality processing specifically for Bulgarian, which is less represented in standard commercial language models compared to English.

2. System Architecture

The designed system follows a classic linear pipeline for processing audio data and text, consisting of three fundamental components: Speech → Speech-To-Text (STT)→ AI Processing → Text-To-Speech (TTS) → Reply.

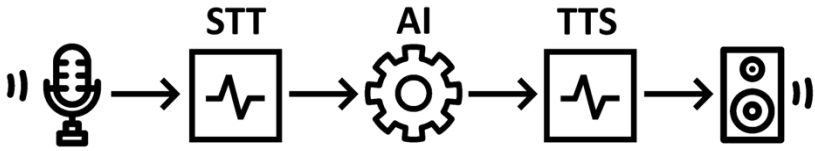


Fig. 1. System Architecture

2.1. Speech-to-Text Module

To transcribe the user's voice into text, OpenAI's Whisper neural network is used. The choice is justified by the fact that the model has excellent support in Bulgarian and can work completely locally (offline), guaranteeing data security and low latency. Depending on the operating system, different software shells are used: Whisper.net for the .NET environment and the official openai-whisper package for Python.

2.2. Intelligent Processing Module (Generative AI)

The assistant core, responsible for semantic analysis and generating a meaningful response, is based on the Google Gemini 2.5 Flash-Lite model using the official Google GenAI SDK. The model is accessed online via an API key. Through System Prompts, the model is configured to act as a university assistant, to respond strictly in Bulgarian and to maintain a concise style (between 2 and 5 sentences), suitable for subsequent voice synthesis.

2.3. C. Text-to-Speech Module

The conversion of AI-generated text into speech is carried out entirely offline in order to achieve maximum speed. The system resources of the respective OS are used: Windows.Media.SpeechSynthesis for Windows environments (using the built-in bg-BG voice pack) and eSpeak-ng on Linux.

3. Software implementation and platforms

The project has been successfully developed and tested in two parallel software configurations:

3.1. Desktop application for Microsoft Windows (C# / WinUI 3)

The Windows implementation is built as a modern graphical application using WinUI 3 and .NET. The architecture is strictly modular and divided into three main services:

WhisperService.cs: Encapsulates the processing of audio files using the Whisper.net library. At initial startup, it automatically downloads the required language core (ggml-medium.bin ~ 1.5 GB). Transcription is performed asynchronously:

```
C#
await foreach (var segment in processor.ProcessAsync(fileStream))
 {   sb.Append(segment.Text);
}
```

GeminiService.cs: Communicates with Google's API by sending the user question along with predefined context for language and answer length.

SpeechService.cs: Uses the built-in capabilities of Windows 10/11 for Bulgarian speech synthesis by directing the generated audio stream to the MediaPlayerElement interface element.

Audio recording is carried out through the NAudio library in 16 kHz, 16-bit, Mono PCM format, which is the optimal input standard for Whisper AI. The graphical interface of MainWindow.xaml provides convenient fields for visualizing the recognized question and the returned answer.

The graphical interface of the Microsoft Windows operating system application along with sample queries is shown in Fig. 2 and Fig. 3.

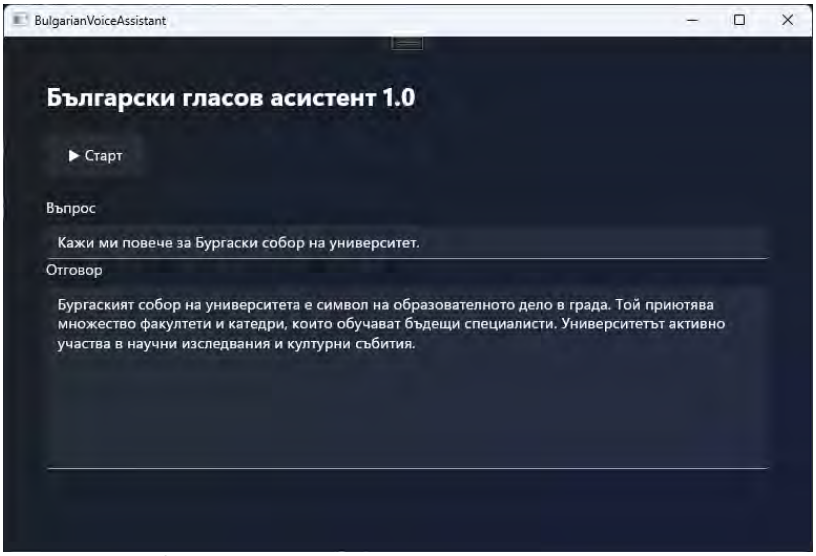


Fig. 2. Sample first experimental query in Windows

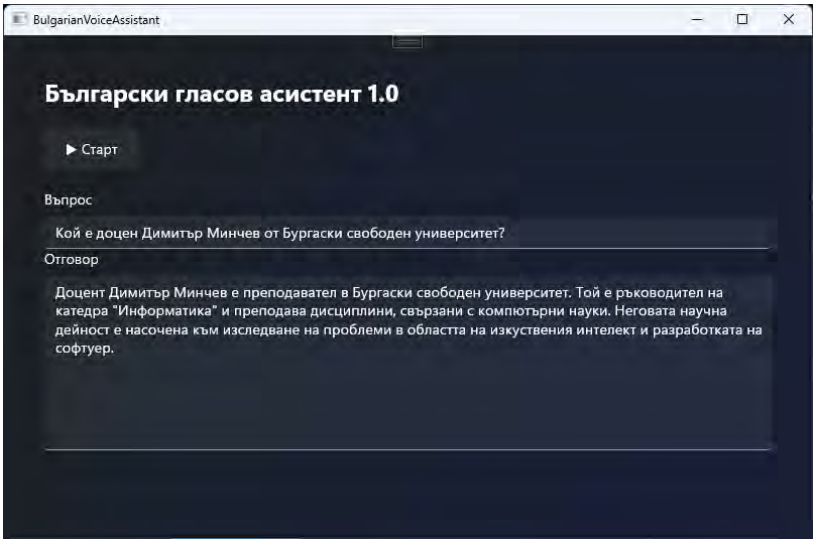


Fig. 3. Sample Second Experimental Request in Windows

3.2. Embedded Linux System (Python / Raspberry Pi)

For portable or kiosk (Kiosk) deployment in the university building, a lightweight version of Python has been developed, optimized for the Raspberry Pi 4/5 hardware platform running Raspberry Pi OS (64-bit).

Audio recording is controlled by the sounddevice library at a sampling rate of 44.1 kHz, after which the data is converted to 16-bit PCM and recorded locally to record.wav.

Local speech recognition is performed by the whisper.load_model("small") model, providing a balance between accuracy and hardware resources of the microcomputer.

Voice synthesis is output through the terminal instrument espeak-ng -v bg -s 150, which allows fine-tuning of the expression rate. The interface in this version is fully console (CLI), initiated by a user event (keystroke).

The text interface of the Linux operating system application along with sample queries is shown in Fig. 4 and Fig. 5.

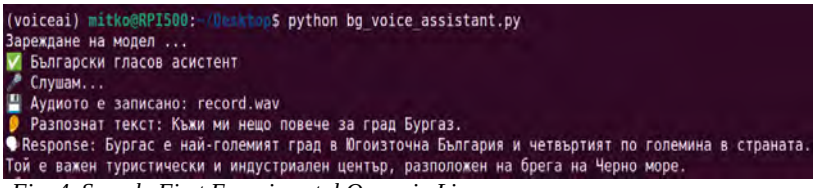


Fig. 4. Sample First Experimental Query in Linux

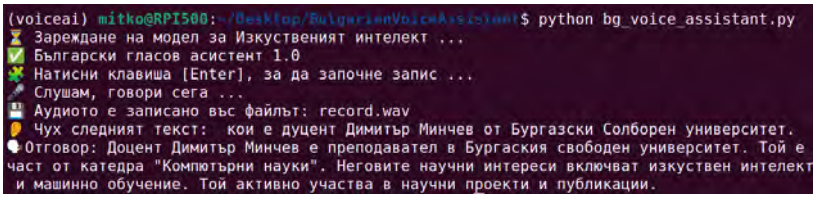


Fig. 5. Sample Second Experimental Query in Windows

4. Benchmarking and experimental results

In the process of testing both platforms, the following advantages and limitations were deduced:

Criteria	***Windows Version (WinUI 3)***	***Linux Version (Raspberry Pi)***
User Interface	*Modern GUI (Mica effects, text boxes)*	*Cantilever (CLI) key-activated*
Whisper Model	*Medium (Higher accuracy, slower processing)*	*Small (Optimized for ARM processors)*
Synthesis Quality (TTS)	*Excellent (Natural voice from Windows OS)*	*Medium (Robotic sound from espeak-ng)*
Mobility	*Limited to desktops / laptops*	*High (IoT integration capability in kiosks)*

Advantages of the development:

- **Natural User Dialogue**: The LLM integration allows the assistant to understand loose wording of questions instead of relying on strictly defined voice commands.
- **Hybrid architecture**: Combining offline components (STT/TTS) with an online model (Gemini) optimizes network traffic and increases security.

Limitations and challenges:

- **Internet connection dependency**: When the connection to the Google Gemini API is interrupted, the system loses its intelligence and cannot generate responses.
- **Noisy environment**: When tested in a real university environment (corridors with background noise), the accuracy of the WhisperSTT

decreases, necessitating the use of directional microphones or software noise filtering.

5. Conclusion and future development

The development of a voice assistant with artificial intelligence is a successful step towards the modernization of the digital ecosystem of Burgas Free University. The project successfully proves that modern software architectures allow voice communication in Bulgarian with a high degree of understanding.

Future work on the project will focus on:

- **Integration with university API systems:** Connect the assistant to the BFU database to check individual grades, exam dates and schedules in real time.
- **Local LLM models:** Migrate from Google Gemini to a fully local language model (e.g. fine-tuned Llama 3 or Gemma for Bulgarian) running on a university server, for full autonomy and independence from external providers.
- **Mobile Apps:** Develop client apps for Android and iOS.

References:

1. Radford, A. et al. (2023). Robust Speech Recognition via Large-Scale Weak Supervision. OpenAI Technical Report. (Достъпно за Whisper модела) .
2. Google DeepMind. (2024). Gemini: A Family of Highly Capable Multimodal Models. Technical Report.
3. Jurafsky, D., & Martin, J. H. (2023). Speech and Language Processing (3rd ed. draft). Stanford University.
4. Russell, S., & Norvig, P. (2021). Artificial Intelligence: A Modern Approach (4th ed.). Pearson.
5. Young, S. et al. (2018). The Dialog System Technology Challenge. Computer Speech & Language.
6. Huang, X., Acero, A., & Hon, H. (2001). Spoken Language Processing: A Guide to Theory, Algorithm, and System Development. Prentice Hall.
7. Microsoft Documentation. (2024). Windows.Media.SpeechSynthesis Namespace. Microsoft Learn.
8. Whisper.net Project. (2024). Open-source .NET bindings for Whisper.cpp. GitHub Repository.

СЪОБРАЖЕНИЯ ПРИ ПРОЕКТИРАНЕТО НА ЗАРЯДНИ СТАНЦИИ ЗА ЕЛЕКТРИЧЕСКИ ПРЕВОЗНИ СРЕДСТВА

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CONSIDERATIONS FOR THE DESIGN OF ELECTRIC VEHICLE CHARGING STATIONS

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Abstract: *Nowadays, energy efficiency has become a top priority, driven by climate change and rising oil prices, especially in countries heavily dependent on imported fossil fuels. This has led to increased interest in the development of charging infrastructure for electric vehicles. As a result, there has been rapid development of charging stations for electric vehicles. Electric vehicles (EVs) are becoming an increasingly preferred choice for both urban and long-distance travel. Modern compact and fast charging stations ensure minimal dwell time and are particularly suitable for use in urban environments and along major thoroughfares. These technological solutions are designed for both fleets and individual consumers, specifically for areas with heavy traffic and optimal power supply conditions. They must meet the dynamically changing requirements of public and private transportation.*

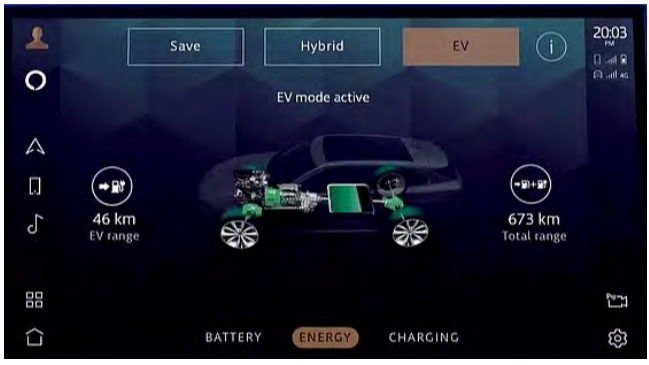
Keywords: *Electric vehicles, charging infrastructure, photovoltaic charging stations*

Хибридното електрическо превозно средство с възможност за зареждане от електрическата мрежа (PHEV) изисква електронна система за захранване, осигуряваща връзка между електрическата мрежа и високоволтовия акумулаторен пакет, разположен в превозното средство. Тази система се състои от две основни части: зарядна станция, наричана още сервизно оборудване за

електрически превозни средства (EVSE) или външно зарядно устройство, и бордово зарядно устройство, интегрирано в самото превозно средство.



Зарядната станция за електрически превозни средства (ECS) представлява елемент от инфраструктурата, предназначен да доставя електрическа енергия за зареждане на електрически превозни средства, свързани към електрическата мрежа, включително електромобили, нискоскоростни електрически превозни средства и хибриди с възможност за външно зареждане. Тя е част от електроенергийната инфраструктура и може да бъде инсталирана на улици, паркинги или в домашни гаражи. Основната ѝ функция е да осигурява електрозахранване за зареждане на батериите на PHEV. Бордовото зарядно устройство е отговорно за крайния етап на процеса на зареждане. То приема променливотоково (AC) захранване от EVSE и го преобразува в необходимия токово-напреженов профил, съобразен с изискванията на акумулаторния пакет.



Предимства на зарядните станции за електрически превозни средства:

- Увеличаването на броя на зарядните станции стимулира продажбите на електрически превозни средства, като намалява т.нар. „тревожност за пробег “.
- Допринасят за намаляване на вредните емисии и подобряване на качеството на околната среда.
- Създават възможности за пряка и непряка заетост в националната икономика.
- Предоставят добри възможности за предприемачество, особено за млади предприемачи, чрез изграждане и експлоатация на зарядна инфраструктура на местно ниво.
- Наличието на различни механизми за финансиране позволява на инвеститорите да намалят първоначалните разходи и да ускорят изграждането на устойчива и широкообхватна мрежа за зареждане.

Очаква се пазарът на инфраструктура за зареждане на електрически превозни средства да нараства със средногодишен темп над 20% през периода 2025–2030 г.



Проектирането на зарядна станция за електрически превозни средства не се изчерпва единствено със свързването ѝ към електрическата мрежа, а изисква внедряване на иновативни решения, съобразени с принципите на устойчивост и удобство при използване. Съгласно изискванията на Международната електротехническа комисия (IEC), прилагането на утвърдени технически стандарти и съвременни технологии представлява основа за развитието на инфраструктурата за електрическа мобилност.

Проектирането на ефективна и удобна за потребителя зарядна инфраструктура предполага отчитане на редица ключови фактори, сред които изборът на подходящо местоположение, управлението на електрозахранването, както и интеграцията със съществуващата електроенергийна система.

Съвременните зарядни станции за електрически превозни средства са разработени с цел да осигурят лесно, надеждно и удобно потребителско изживяване, като същевременно гарантират ефективно управление на енергията. Те предлагат разнообразни функционалности, съобразени с различните изисквания на собствениците на електрически превозни средства. По - долу е представен обобщен преглед на основните функции, характерни за този тип станции:

Управление на захранването – Зарядните станции за електрически превозни средства следва да бъдат проектирани така, че да оптимизират разпределението на електроенергията и балансирането на натоварването. Това позволява ефективно използване на наличния енергиен ресурс и предотвратява претоварване на електрическата мрежа.

Управление на потребителите – Ефективното управление на потребителите е съществен елемент от всяка система за зареждане на електрически превозни средства. Независимо от броя на потребителите, е необходимо да се осигури надежден контрол на достъпа и възможност за персонализиране на взаимодействието със системата. Съществено значение има и наличието на интуитивен потребителски интерфейс, включващ мобилни приложения, възможности за онлайн плащане, резервации и други дигитални услуги.

Управление на хардуера – От съществено значение е зарядното оборудване да бъде надеждно защитено от атмосферни въздействия и несанкциониран достъп, с цел гарантиране на неговата дълготрайност и предотвратяване на повреди, причинени от външни фактори или вандализъм.

Достъпност и местоположение – Осигуряването на универсален достъп е ключов аспект при проектирането на зарядни станции. Това включва възможности за използване от хора с намалена подвижност, като достъп за инвалидни колички и наличие на инструкции на брайлова азбука. Същевременно е важно станциите да бъдат разположени на локации с добра транспортна достъпност и изградена пътна инфраструктура.

Поддържаща инфраструктура – За повишаване на сигурността и удобството при използване е необходимо изграждането на подходяща съпътстваща инфраструктура, включително ефективно осветление и системи за видеонаблюдение.

Разнообразие от изходи – Съвременните зарядни станции трябва да поддържат различни режими на зареждане, включително променлив ток (AC) и постоянен ток (DC), както и да разполагат с множество изходи, позволяващи обслужване на различни типове превозни средства и сценарии на употреба.

Методи на плащане – За обществените зарядни услуги сигурната и надеждна обработка на плащанията е от съществено значение. Необходимо е да се поддържат разнообразни платежни методи (напр. банкови карти, мобилни приложения, безконтактни разплащания), за да се гарантира достъпност и удобство за широк кръг потребители.

Предизвикателства при проектирането на зарядни станции за електрически превозни средства
Проектирането на зарядна инфраструктура е съпроводено с редица технически, експлоатационни и регулаторни предизвикателства, свързани с безопасността, сигурността и бъдещата интеграция в електроенергийната система. Основните от тях включват:

- **Безопасност и киберсигурност** – Необходимо е внедряване на надеждни механизми за защита срещу кибератаки и неоторизиран достъп, както и гарантиране на сигурността на обмен и съхранението на данни. Особено внимание следва да се отдели на защитата на цифровите платежни системи и комуникационните интерфейси.
- **Интеграция в електроенергийната мрежа** – Ефективното управление и балансиране на натоварването е ключово за предотвратяване на претоварвания, особено в райони с ограничен капацитет на електроенергийната инфраструктура.
- **Осигуряване на бъдеща съвместимост** – Зарядните станции трябва да бъдат проектирани с оглед на бъдещото развитие на технологиите при електрическите превозни средства, като се гарантира тяхната съвместимост, мащабируемост и възможност за надграждане.
- **Избор на местоположение** – Определянето на подходящи локации за изграждане на зарядни станции следва да отчита наличността на терени, достъпа до електроенергийна инфраструктура, както и съответствието с местните нормативни изисквания и устройствени планове.

Преодоляването на тези предизвикателства изисква прилагането на иновативни проектантски решения и стратегическо планиране, насочени към подпомагане на устойчивото развитие на пазара на електрически превозни средства.

Проектирането на зарядна станция за електрически превозни средства предполага цялостен и перспективен подход, който отчита бъдещото развитие на технологиите и тяхната ефективна интеграция с електроенергийната мрежа, като същевременно гарантира високо ниво на безопасност. Инфраструктурата на тези станции следва да поддържа както зареждане с променлив ток (AC), така и с постоянен ток (DC), с оглед удовлетворяване на различните експлоатационни изисквания.

Висококачественият инженерен дизайн, съобразен с международните стандарти на IEC, създава предпоставки за успешно преодоляване на съществуващите предизвикателства в сектора и допринася за по-широкото внедряване на електрическите превозни средства.

С нарастването на търсенето на електрически превозни средства става все по-необходимо зарядните станции да бъдат проектирани с оглед на бъдещите стандарти и ефективната им интеграция в електроенергийната мрежа. Това включва осигуряване на надеждна свързаност за дистанционно наблюдение и управление чрез съвременни комуникационни технологии, като 5G, внедряване на интелигентни системи за управление на натоварването, както и поддръжка на двупосочно зареждане и пренос на енергия от превозното средство към мрежата (Vehicle-to-Grid, V2G).

Прилагането на модулен подход в проектирането на зарядни станции позволява постигането на по-голяма гъвкавост и адаптивност към разнообразните потребности на потребителите. Това включва възможност за конфигуриране на станции с поддръжка както на променлив ток (AC), така и на постоянен ток (DC), както и интегриране на различни нива на зареждане – Ниво 1, Ниво 2 и бързо зареждане с постоянен ток – в рамките на една система. По този начин се осигурява съвместимост с различни типове превозни средства и се оптимизира времето за зареждане в зависимост от конкретния сценарий на използване.

За да се гарантира дългосрочната и надеждна експлоатация на зарядните станции за електрически превозни средства, е необходимо да се прилагат комплексни мерки за сигурност и безопасност. Това включва използване на защитени корпуси, устойчиви на

неоторизиран достъп, внедряване на съвременни протоколи за киберсигурност с цел предотвратяване на хакерски атаки и защита на данните, както и стриктно спазване на действащите стандарти за електрическа безопасност. Допълнително, регулярната поддръжка и своевременните софтуерни и хардуерни актуализации допринасят за повишаване на надеждността и удължаване на експлоатационния живот на системите.

За осигуряване на стабилна, безопасна и съвместима работа на зарядната инфраструктура е от съществено значение спазването на стандартите на Международната електротехническа комисия (IEC). Те обхващат ключови аспекти като електрическа безопасност, електромагнитна съвместимост, комуникационни протоколи и методи за изпитване. Прилагането на тези стандарти гарантира съответствие с международните изисквания за безопасност, ефективност и оперативна съвместимост. По този начин се повишава качеството на услугата и се укрепва доверието на потребителите към инфраструктурата за електрическа мобилност.

Различните метеорологични условия налагат при проектирането на зарядни станции за електрически превозни средства да се предвидят както външни, така и вътрешни инсталации. Външните зарядни станции следва да бъдат устойчиви на атмосферни влияния и оборудвани с ефективни системи за термично управление, които да осигуряват надеждна работа при екстремни температури и други неблагоприятни условия на околната среда. От своя страна, вътрешните станции трябва да поставят акцент върху оптималното използване на пространството, ефективната вентилация и лесната достъпност за потребителите.

От съществено значение е и внедряването на сигурни механизми за удостоверяване, които да гарантират надеждно и удобно потребителско изживяване при зареждане. Това включва интеграция на различни методи за автентикация, като RFID карти, мобилни приложения и QR кодове, комбинирани със съвременни комуникационни протоколи за дистанционно наблюдение и управление. Допълнително, използването на дигитални платежни платформи и многоезични потребителски интерфейси допринася за по-висока достъпност и значително подобрява цялостното потребителско изживяване.

Преходът към електрическа мобилност изисква изграждането на надеждна и усъвършенствана инфраструктура за зареждане на

електрически превозни средства. Този процес включва разнообразни решения за зареждане – от домашни зарядни устройства Ниво 2 до високоефективни обществени станции Ниво 3, като всяко от тях е проектирано да отговори на различните потребности на собствениците на електромобили. Разбирането на технологиите за зареждане и свързаните с тях проектни изисквания е ключово за ефективното функциониране на интегрирана мрежа от зарядни станции.

Ниво 2 (208–240 V AC) - Предназначено както за домашна, така и за обществена употреба, това ниво на зареждане осигурява по-висока скорост на зареждане при напрежение 208–240 V AC и предоставя приблизителен пробег от 10–25 мили на час зареждане.

Ниво 3 (бързо зареждане с постоянен ток – DC) - Позволява значително по-бързо зареждане, като може да осигури до около 200 мили пробег за 15–30 минути. Подходящо е основно за обществени зарядни станции и изисква високопроизводителна инфраструктура за постоянен ток, включително специализирано електрозахранване и оборудване.

Както е известно, AC зарядните станции (Ниво 1 и Ниво 2) са проектирани да подават променлив ток (AC) към бордовото зарядно устройство на електрическото превозно средство, което впоследствие го преобразува в постоянен ток (DC) за зареждане и съхранение в батерията. Тези зарядни станции изискват специфични електрически конфигурации, за да се управлява ефективно енергийната консумация и да се гарантира безопасно и надеждно захранване.

Съображения при проектиране и захранване на DC бързи зарядни станции: DC бързите зарядни станции са предназначени за директно подаване на високоенергиен постоянен ток (DC) към батерията на електрическото превозно средство, като заобикалят бордовото зарядно устройство. Поради това те изискват значително по-сложна и мощна инфраструктура, включваща трансформатори, силови електронни преобразуватели, кабели за високо напрежение и ефективни системи за охлаждане.

Този тип станции преобразуват променливия ток (AC) от електрическата мрежа в постоянен ток (DC) на място и го доставят директно към батерията, което позволява значително по-кратко време за зареждане. Поради високата си мощност и скорост на зареждане, DC бързите зарядни станции са особено подходящи за

дълги пътувания и интензивна употреба в обществени зарядни локации.

Използването на зарядните станции следва да бъде ефективно, надеждно и лесно за потребителите.

Необходимо е прилагането на ефективно управление на захранването и балансиране на натоварването, с цел оптимизиране на потреблението на електрическа енергия и предотвратяване на претоварвания в системата.

Здравата конструкция и оборудването, устойчиво на атмосферни влияния, осигуряват безпроблемна експлоатация при различни климатични условия.

Лесните за използване интерфейси, разнообразните методи за плащане и добрата достъпност значително подобряват цялостното потребителско изживяване.

Също така е от съществено значение да се осигурят адекватно електрозахранване, ефективно осветление и ясна сигнализация. Чрез прилагането на тези мерки зарядните станции могат да предоставят надеждно, удобно и съвместимо с изискванията изживяване, като по този начин стимулират по-широкото навлизане на електрическите превозни средства.

Това включва широк спектър от типове превозни средства и различни капацитети на батериите. За да се отговори на това разнообразие, зарядните станции трябва да предвиждат:

- Осигуряване на комбинация от възможности за зареждане – Ниво 1, Ниво 2 и бързо DC зареждане – с цел удовлетворяване на различните потребности на потребителите.
- Проектирането на станцията трябва да бъде съобразено с различни капацитети на батериите и конструктивни особености на превозните средства.

С оглед на бързо развиващата се индустрия за електрически превозни средства, проектантите на зарядна инфраструктура трябва да гарантират:

- Прилагане на модулни конструкции, които позволяват лесно надграждане, актуализация и бъдещо разширяване на системите.
- Интеграция на нововъзникващи технологии, като Vehicle-to-Grid (V2G) и безжично зареждане.
- Приоритизиране на киберсигурността с цел защита на потребителските данни и предотвратяване на

потенциални заплахи, свързани с поверителността и сигурността на информацията.

Стартирането на зарядна станция за електрически превозни средства представлява значителна инвестиция. За да се повиши нейната икономическа ефективност, операторите следва да разгледат различни възможности за финансиране, включително:

Използване на държавни програми и схеми за подпомагане, които намаляват разходите за изграждане на инфраструктура.

Сътрудничество с частни организации чрез публично-частни партньорства (PPP) или корпоративни спонсорства.

Възползване от данъчни облекчения и стимули, свързани с инвестиции в електрическа мобилност и устойчив транспорт.

Инвестиране чрез зелено финансиране, както и използване на безвъзмездни средства от международни и местни организации, насърчаващи устойчивото развитие и електрическия транспорт.

Изводи

За да се осигури безпроблемно, ефективно и ориентирано към бъдещето потребителско изживяване при зареждане на електрически превозни средства, проектантите и разработчиците на зарядна инфраструктура следва да вземат предвид следните ключови аспекти:

- Внедряване на модулни конструкции, които позволяват лесна адаптация към бъдещи технологични подобрения и нововъзникващи решения.
- Приоритизиране на киберсигурността и защитата на личните данни чрез надеждни протоколи за сигурност и поверителност.
- Прилагане на стратегии за интелигентно управление на натоварването, както и интеграция на възобновяеми енергийни източници, като, например, слънчеви панели, с цел устойчиво функциониране.
- Стриктно съобразяване с развиващите се международни стандарти и регулаторни изисквания.
- Осигуряване на съвместимост с разнообразни типове електрически превозни средства и различни конфигурации на зареждане.
- Редовно актуализиране на хардуера и софтуера на зарядните системи с цел поддръжка на най-новите технологии и модели превозни средства.

- Събиране и анализ на обратна връзка от потребителите и данни за използването, с цел непрекъснато подобряване на услугата.
- Внедряване на интуитивни потребителски интерфейси, дигитални методи на плащане и функции за достъпност, които подобряват цялостното потребителско изживяване.
- Изследване и прилагане на иновативни решения, като мобилни зарядни станции, за разширяване на достъпността и гъвкавостта на инфраструктурата.

References:

1. https://pulseenergy.io/blog/ev-charging-station-design
2. https://uta.pressbooks.pub/sustainablemobility/chapter/chapter-7-design-of-charging-infrastructure/
3. https://pulseenergy.io/blog/ev-charging-station-design Introduction to Electric Vehicle Charging Station Architecture
4. https://www.kviconline.gov.in/pmegp/pmegpweb/docs/commonprojectprofile/EVChargingStation.pdf
5. https://www.sciencedirect.com/topics/engineering/ev-charging-station
6. Радостин Долчинков, Камен Сейменлийски, Иван Попов, Безопастност на електрически автомобил. Сборник с доклади от Международна научна конференция „Черно море - Врата и много мостове“, 2022, Бургас, изд. БСУ,, ISBN: 978-619-253-017-4, с. 533 - 540

ANALYSIS OF HAZARDS ASSOCIATED WITH THE OPERATION OF TAILINGS STORAGE FACILITIES IN THE REPUBLIC OF BULGARIA

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Abstract: *This report aims to analyze the possible dangers in the operation of tailings impoundments in a certain geographical region of the Republic of Bulgaria - specifically in the municipalities of Zlatitsa, Pirdop, Chelopech, Mirkovo and Chavdar and to provide a proposal for the improvement of their activities. The protection in case of disasters resulting from the operation of tailings impoundments in the Republic of Bulgaria, the activities for protection from dangers in the operation of tailings impoundments, as well as the possibilities for optimizing the protection from dangers in their operation are considered.*

Keywords: *Tailings impoundments; Disaster risk management; Hazard protection*

The subject of the study of the work is the nature of possible dangers during the operation of tailings impoundments in a certain geographical region of the Republic of Bulgaria.

The object of the study of the work is the facilities for storing mining waste from enterprises in the region in question.

The protection of the population in the event of disasters in the mining industry is a priority activity of all producer countries. Given the geological and geographical characteristics, the Republic of Bulgaria falls within this scope, especially in the focus of the disposal of waste from the activity. It is known that in the recent past the problems in the implementation of this activity were shrouded in strict secrecy, as happened in the tragedy in the village of Zgorigrad in 1966. The biggest weakness of the previous administrations of the country in the field of prevention in these types of activities is that the scientific potential of the nation was not used to a sufficient extent, the proposals and opinions of scientists were ignored, and conscious and targeted disinformation of the public was carried out.

Protection from hazards in the operation of tailings facilities is possible only with the full use of the country's scientific potential, under conditions of publicity, transparency, public awareness, dialogues and public discussion, providing feedback, and the increasingly active involvement of society in solving the problems of its own protection from all harmful factors.

Therefore, informing the public about what happened, where it happened, how it happened, who it affected and what consequences may be present is a priority task for both operators and the state. Preventing panic and mass hysteria, organizing, motivating and involving people in the process of eliminating the consequences of disasters are prerequisites for quickly dealing with the crisis situation [1].

According to [6], danger is defined as the possibility of something unpleasant happening - trouble, threat. The nouns risk, threat, threat, riskyness, fate, mishap, doom, probability, possibility are presented as synonyms of the term.

Since the early 1990s, the United Nations Economic Commission for Europe (UNECE) has been committed to the prevention, preparedness and response to industrial accidents, especially those with transboundary consequences in the field. The 1992 ECE Convention on the Transboundary Effects of Industrial Accidents [5] helps to protect people and the environment from such accidents by preventing them as far as possible, reducing their frequency and severity and mitigating their consequences. Problems related to the prevention of accidental water pollution are considered in close cooperation with the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes.

Industrial accidents at mining waste management facilities (MWMFs) can indeed lead to accidental water pollution. MWMFs store large quantities of mine waste, which is generated as a by-product of mineral extraction. As such, they pose a serious threat to people and the environment, especially in the case of improper design, operation or management. Thus, an accident can lead to uncontrolled tailings flow, dangerous landslides or the release of hazardous substances, causing significant environmental disasters. The devastating human and environmental consequences of such incidents, as well as their widespread and severe transboundary consequences, have been demonstrated by significant accidents in recent years in the ECE region, such as the failure of a tailings dam at a mining facility in Baia Mare, Romania, in 2000, and more recently the spill of aluminium sludge in Kolontar, Hungary, in 2010, or the accident at the Talvivaara mining company in Finland in 2012.

The efficient and safe disposal of mining waste poses technical and environmental challenges. Each facility is unique due to the basic design principle based on the natural terrain of the site, which requires a site-specific and well-founded approach to ensure that the TMF is safe, environmentally sound and economical.

Mining waste is a fine-grained waste material remaining after the extraction of metals and minerals through technical processes. The material is discarded in the “last part” of the process with a particle size typically in the range of 10 μm to 1.0 mm.

A mining waste storage facility is a facility that may include a tailings pond (waste collection tank and basin), decantation structures and spillways. A mining waste storage facility may also be an open pit, dry storage facility, ponds or underground storage facilities.

A tailings facility is an embankment or structure for the disposal of tailings. The term “tailings facility” includes embankments, dams or other containment structures constructed in a controlled manner and designed to assist in the settling of waste and the retention of tailings and process water.

A tailings pond is the space/storage volume created by a tailings pond or dam in which mining waste is deposited and stored.

According to other sources, a tailings pond is a facility used to store by-products of mining operations after the ore has been separated from the rock. Tailings ponds are designed for permanent storage, meaning "to stay there forever." Copper, gold, uranium, and other mining activities produce many different types of waste, many of which are toxic, which poses a number of hazards in long-term storage.

There are approximately 3,500 active tailings ponds worldwide, although there is no complete record and the total number is uncertain. As of 2000, these facilities experienced an average of 2-5 major incidents per year and 35 minor incidents per year.

A tailings pond is built up gradually over the life of the associated mine. Typically, a base or initial wall is constructed, which is gradually raised as it is filled with a mixture of water and waste. The materials used to erect the wall may include the sediments themselves and soil. The specific design of the tailings pond depends on the topology, geology, climate, type of sediments and cost.

In these facilities, the rule of using the available natural relief of the respective area is followed. Depending on the relief of the location area, the following types of tailings ponds are distinguished (Fig. 1):

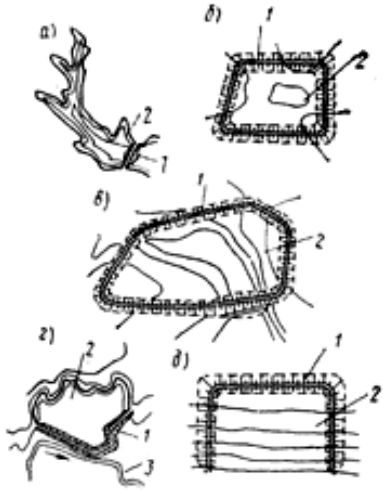


Fig. 1. Types of tailings ponds.

a) – located in a ravine; b) – located in a plain; c) – located in mixed terrain (ravine and plain); d) - located in a floodplain; e) – located on a sloping terrain; 1 – dam wall; 2 – tailings pond bed; 3 – river

a) located in a ravine - are located in ravines or ravines blocked by a dam;

b) located in a plain - are located on a flat surface with a dip along the perimeter. The advantage of a flat tailings pond is that it is not necessary to remove natural runoff and build expensive drainage facilities for this purpose;

c) located in mixed terrain - are located in plains crossed by ravines that are blocked by dams and the plain is collapsed;

d) located in a floodplain - they are located within the boundaries of riverbeds with immersion on two or three sides depending on the terrain;

e) located on sloping terrain - they are located on sites protected on three sides by dams, and the fourth is the slope itself [7].

There are also:

- excavated - are located in volumes of old quarries or mines; Here it is possible to store waste without the presence of dam walls - Fig. 2;

- valley - are distinguished on the basis of a concave oval shape of the relief, surrounded by hilly or mountainous slopes; in them storage is also possible without the presence of a dam wall or with the presence of a low wall.

The total number of tailings impoundments on the territory of the Republic of Bulgaria is 33, of which over a third are operational, and the rest are unreclaimed and reclaimed. Tailings dams have also been constructed

at thermal power plants and some of the quarries for the extraction of inert materials [9].



Fig. 2. Tsar Asen Mine.

Operating tailings facilities:

• "Benkovski 2", "Elatsite Med" (42.637147° N 24.03594° E)

• "Chelopech", "Chelopech Mining", owned by "Dundee Precious Metals" (42.668458° N 24.082804° E)

• "Lyulyakovitsa", "Asarel Medet" (42.548844° N 24.097996° E)

• "Kaleto" (42.661452° N 24.173913° E)

• "Pirdop", "Arubis Bulgaria" (42.724712° N 24.17209° E)

• Rudozem 2, Gorubso ROF (41.505235° N 24.844272° E)

• Erma Reka, Minstroy Holding (41.418803° N 25.025074° E)

• Lucky 2, Elatsite Med (42.637147° N 24.03594° E)

• Kardzhali 2, Gorubso Kardzhali (41.857767° N 25.402633° E)

• Senovo, Kaolin AD (43.667359° N 26.374483° E)

• Vetovo, Kaolin AD (43.671767° N 26.250157° E)

• Kaolinovo, Kaolin AD (43.626788° N 27.092242° E)

• Odrtsi, Euromangan (43.440884° N 27.950281° E)

• Hemus M

Unreclaimed tailings ponds:

• Medet, MBS, the largest tailings pond in the Balkans (42.61937° N 24.17726° E)

• Buhovo, old uranium tailings pond (42.755489° N 23.581874° E)

• Metallurgical waste dump slag "Kremikovtsi" (42.743687° N. lat. 23.569064° E.)

• "Benkovski 1", "Elatsite Med" (42.653625° N. lat. 24.024782° E.

• “Lucky 1”, “Elatsite Med” (41.5126° N 24.5011° E)
• “Osogovo”, “MOK Osogovo” (42.266155° N 22.464327° E)
• “Gueshevo 1” (42.235762° N 22.46924° E)
• “Gueshevo 2” (42.247478° N 22.474433° E)
• “Gueshevo 3”

Reclaimed tailings ponds:

• “Eleshnitsa” tailings pond (41.846899° N 23.63657° E)

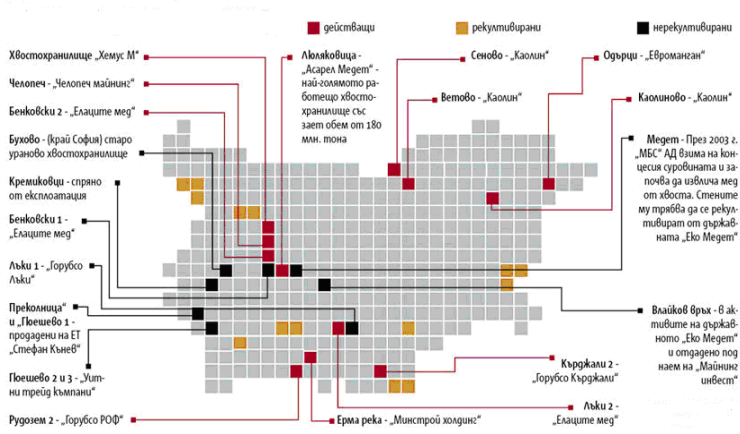


Fig. 3. Tailings impoundments in the Republic of Bulgaria.

Pursuant to the Council of Ministers No. 140/1992, the ineffective sites subject to closure and technical liquidation or conservation, and for the liquidation of the consequences of the extraction and processing of ores, are carried out on the basis of working projects adopted by the Interdepartmental Expert Council (MES) at the Ministry of Economy.

The control of the condition of the reclaimed tailings impoundments on the territory of the country by the bodies of the Ministry of Environment and Water is carried out by the Regional Inspectorate for Environment and Water on site, with the monitoring data being transmitted to them and processed by the Executive Agency for the Environment (EEA).

All operating tailings impoundments are designed by specialized teams of designers, built and operated on the basis of approved working projects that guarantee their sustainability and safety. The main designers of these types of hydrotechnical facilities are obliged to carry out author's control of the tailings ponds, both during their operation and after its termination. In parallel with this control and the internal control of the tailings pond user, interdepartmental committees with representatives from various institutions carry out specialized inspections of the condition of the tailings

ponds annually. Control over compliance with the working designs and monitoring of the facilities is also carried out annually by the Regional Inspectorate for Environment and Water (RIEW) on site.

The work on bringing the operating tailings ponds in the country into compliance with the regulatory requirements has already begun, with some of the mining enterprises (Chelopech, Asarel, Elatsite-med, etc.) already at an advanced stage. Following training under an EU-funded twinning project, tailings facility operators are now carrying out the necessary preparations and activities related to waste classification and tailings facility categorization, updating their management plans and emergency plans, monitoring facilities, providing the necessary financial guarantees for closure and liquidation of sites, etc. [9].

If any of the operating tailings facilities or operating mining waste facilities (dumps, landfills, etc.) fail to comply with the requirements of the Directive [2], the sanctions provided for in the law will follow, including its closure and cessation of the company's activities in the extraction and primary processing of subsoil resources.

The construction of tailings impoundments must take into account the requirements of the Spatial Planning Act (SPA) [4], the Subsoil Resources Act (SRA) [3], the Mining Waste Management Ordinance, the Design Standards for Concrete and Reinforced Concrete Structures for Hydraulic Facilities, the Design Standards for Retaining Walls, the Design Standards for Hydraulic Facilities, Eurocode 2, 7 and 8, BDS EN 1990 and others [8].

The construction, operation and closure of tailings impoundments is carried out on the basis of projects that guarantee short-term and long-term safe disposal of waste, in accordance with Art. 82 of [3] in their part for construction, operation and closure of mining waste facilities. They offer solutions that ensure minimal and, if possible, subsequently no monitoring, control and management of the closed mining waste facility. The implementation of the projects must lead to the prevention or minimization of long-term negative effects on the environment and human health. A guarantee of long-term geotechnical stability of the facilities, including their above-ground parts, is also required [8].

For all mining waste facilities, including tailings impoundments, which are construction works within the meaning of [4], all requirements of the ZTA related to the design, construction, commissioning and construction and installation works during closure shall be complied with. The operator shall submit the valid construction permit to the Minister of Energy, when such is required under the ZTA.

Hydrotransport system

In the hydrotransport system, the water flow carries with it small pieces of waste from production in a pipeline. Usually, transportation is carried out by pumping the homogeneous mixture. This is a widely used type of transport both for minerals from the place of extraction to the processing plant, and for the removal of waste suspensions from enrichment plants to the place of their storage and treatment in tailings ponds. The transported medium is water with dispersed solid mineral particles or fibrous organic and inorganic waste substrates.

Water retaining walls

To enclose the sedimentation pond, in which the tailings settle and the process water is clarified, water retaining walls are built. Usually, the technology of phased construction of earthen and washout retaining walls is adopted for tailings ponds. The initial wall reaches a certain elevation to ensure the tailings intake during a given period of mining and enrichment, after which the wall is gradually upgraded to increase the capacity of the tailings pond.

Anti-filtration devices

Filtration is associated with a certain water level in the barrier wall. In cross section, it represents a depression curve. Below it, the soil parameters deteriorate and filtration pressure occurs, which worsens the stability of the slopes. Thus, at high filtration rates, various deformations are observed.

There are four types of anti-filtration devices. One type has a screen made of clay materials with a filtration coefficient Kf=10-7÷10-8cm/s, and the wall is made of water-permeable soil - ballast, sand or clay sand. Another type of device uses a non-soil screen made of reinforced concrete, asphalt concrete or synthetic materials. The third option is with a vertical or inclined core of clay materials with Kf=10-7÷10-8cm/s, with the side prisms being made of ballast, sand or clay sand. And the fourth type is with diaphragms of concrete, asphalt concrete, polymer foil or metal, and the side prisms are as in the previous type. Concrete and reinforced concrete diaphragms, as well as screens, are made of concrete with a strength of not less than 20MPa and a water density of 0.02÷0.03 of the operating head.

When the wall is built on a water-permeable base, sumps are made to reduce filtration. They are made of clay material and represent a horizontal extension of the core or screen. Their length is (1÷1.5)N, where N is the head of the wall. The thickness is determined by the maximum permissible gradient of the head and should not be less than 0.5m.

Drainage system

In the walls of the tailings dams, drains reduce the depression curve and increase the resistance of the air slope. They drain the water that is filtered through the body and base of the wall, without allowing leakage along the air slope of the embankment, thus preventing freezing and filtration deformations. Drains are built at the base of the air slope from a drainage body, a backflow filter and a water drainage collector.

Drains are: drainage prism (built in the channel part of the wall from rock material), layered drainage (when the air slope is submerged by the waters released from the spillway), pipe drainage (where the wall will not be submerged), horizontal drainage (from longitudinal and transverse drainage layers) and combined drainage of the listed types. The water retaining wall can also be built without drainage in the presence of a screen, core or diaphragm with the removal of filtration water, also when the air part of the embankment is made of coarse-grained stone material.

Overflow devices

The removal of clarified water from the tailings pond is done through overflows. They have an approach, an inlet, a transit and an outlet part. The specific water quantity of the overflow facilities is from 50 to 120m3/s for rock and semi-rock base and from 10 to 70m3/s for non-rock base. Overflow facilities in the body of the wall are built if it is concrete. Then they can be surface, siphon and pipeline. However, when the walls are bulk, as is usually the case with tailings ponds, the overflow facilities are built outside the body of the wall. They are called slope overflows. They are of several types according to the type of their inlet part. In frontal spillways, the spillway edge is perpendicular or obliquely located to the horizontals. They increase the length of the spillway front. In trench spillways, the location is in the direction of the horizontals. They are used to increase the length of the spillway edge. The transit part can be a rapid flow with multistage thresholds, with a shaft or tunnel.

As it became clear, in large industrial sites there are slag heaps, tailings ponds and embankments, in which the sedimentation of circulating industrial waters, containing in addition to mechanical impurities and hazardous substances, takes place. Breakages in their walls can cause flooding of settlements and pollution of areas and water sources.

Potential danger of major industrial accidents with the formation of highly toxic environmental pollution can occur in the event of natural disasters, emergency shutdowns and/or low technological discipline. These reasons are a prerequisite for the occurrence of accidents of various nature and scale, some of which are accompanied by the destruction of individual

technological lines or entire sites, with the contamination of large areas with hazardous substances and human casualties.

In summary, it is clear that major incidents related to the operation of tailings dams can occur as a result of breaches in the walls of slag heaps and tailings dams in some large industrial sites.

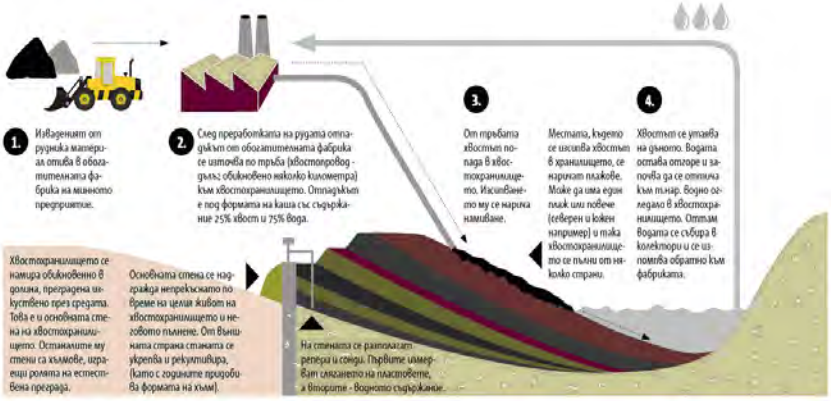


Fig. 4. Technological process of extraction and processing of minerals

Old tailings ponds, filled without taking into account filtration and other factors, often become sources of environmental hazards, including sources of pollution of groundwater and the atmosphere (for example, in dust formation). Tailings ponds can also be a source of acid leaching into the soil, which leads to the constant need for monitoring and treatment of water passing through and around the tailings pond.



Fig. 5. The intact tailings pond in Hungary



Fig. 6. The ruptured wall of a tailings dam in Hungary

Failure modes

An important parameter for the reliability of a tailings dam is the safety factor. Its calculation requires an analysis of the potential failures of the embankment acting as a wall. There are a number of common failure modes to which these embankments may be vulnerable. These include slope failure from overloading (overtopping), failure of main pipelines, erosion, and liquefaction. Each failure mode can lead to partial or complete instability of the facilities.

Rotational sliding

Rotational sliding, so named because the damaged surface appears as a segment of a horizontal cylinder, can lead to slope failures ranging from local spalling of the tailings dam in random areas along the embankment to massive landslides extending over the entire structure. In general, for a stable slope, the shear force resisting movement along a potential failure surface exceeds the shear stress tending to cause movement. Instability occurs when the shear stress across the failure surface equals the shear strength. Specifically, causes of failed circulation may include changes in the water table, changes in the permeability of the foundation materials, embankment failures caused by vibration or impact during loading, and final disposal of the materials.

Foundation Failure

Foundation failures are not uncommon among tailings dam structures. When a weak layer of soil or rock exists at a shallow depth in the foundation beneath the structure, on-plane movement will occur, exceeding the shear strength of the soil in the weak layer.

Overflow

One of the most common causes of tailings dam overflow is heavy rain. Overflow usually occurs when improperly diverted surface water flows or excessive stormwater flow enter the tailings impoundment volume, thereby exceeding the containment capacity. Because tailings impoundments

are made of highly erodible materials, the friction caused by rapid flow through the unprotected embankment can cause the ridge to erode rapidly and breach the wall, allowing water to escape quantities. In addition, the rapid increase in pore pressure combined with the large inflow of rainwater can lead to the liquefaction of unconsolidated (unreinforced) sands and silts. A sustained flow over the crest of the embankment can lead to a serious breach and the leakage of the contents of the tailings dam.

Erosion

In areas of heavy rainfall, some form of erosion protection is usually required. Embankments can be susceptible to erosion damage in two main areas, the embankment pavement and the embankment walls. Erosion at the contact line between the embankment and the abutment can result from rainwater flow being concentrated there and is a consequence of faulty construction or maintenance. This type of damage is usually prevented by the method of rainwater diversion. As a result of erosion of the walls of the tailings dam, bursting, rupture due to destruction of the contour of the embankment crest can occur. Again, maintenance and periodic placement of the deposited material along the contours can prevent this type of failure.

Cavitation

Violation refers to subsurface erosion along the seepage path, within or below the embankment walls, that occurs when a low-pressure leak occurs, allowing concentrated flow. Cavitation can result from seepage of the embankment surface at a rate sufficient to break the surface itself. The resulting void space causes progressive erosion extending inward toward the source of seepage. In the worst case, seepage can lead to local or general failure of the embankment or the base of the tailings pond.

Liquefaction

Liquefaction is one of the most common problems encountered in tailings ponds. Since the deposits are usually composed of unconsolidated, similar-sized grains, they are susceptible to temporary suspension in water. Liquefied ore wastes can behave like viscous fluids, so they flow through narrow openings and over considerable distances. Accordingly, even small failures of tailings impoundments can result in significant releases of the contained materials.

Factors that influence the potential for liquefaction include:

- Soil type - Materials uniform in grain size, particularly fine sand size, are most susceptible to liquefaction.

- Relative density or compactness - For a given material, the more compact or dense it is, the more resistant it will be to liquefaction.

- Initial pressure limitation at the time of dynamic stress - This makes it possible in certain areas to prevent liquefaction by applying overburden to bulk deposits.

- Intensity and duration of ground shaking - Liquefaction can occur due to an intense earthquake or due to sustained ground motion.

- Location of water table - high water table has a detrimental effect. Therefore, a tailings facility constructed on a perfect foundation or a dam with a phreatic line, kept low by providing suitable internal drainage features, can have a significantly reduced potential for liquefaction.

By incorporating drainage facilities, maintaining a low water table, and compacting the fill materials during construction, density, saturation, and pressure confinement can be controlled to reduce the likelihood of liquefaction. If the tailings facility is constructed of fine sand, compacting these sands will increase their density and reduce their susceptibility to liquefaction. Compaction to obtain a relative density of 60% or more provides reasonable protection. Therefore, provided that the bulk materials have a relative density of 60% or more, or provided that the phreatic surface is maintained well below the surface of the embankment, it is safe from liquefaction. Calculations for each individual site are required during design.

Public disclosure of tailings impoundment incidents is poor. A large number remain unreported or lack basic facts when reporting. There is no available database of historical accidents.

Conclusions

Based on the presented features of the technological process, possible hazards, as well as the listed failure modes, the following problems can be identified in the operation of tailings impoundments:

1. In the hydrotransport system and pumping stations:

- deformations along the route of the main and wash tailings pipelines due to subsidence of the terrain;

- deformations in the tailings pipelines themselves due to blasting work near the tailings pipeline routes, as well as wear and tear of the pipes themselves;

- compromise of facilities in the hydrotransport system during catastrophic rainfall and snowmelt;

- breaks in the joints, connections and fittings of the main and distribution tailings pipelines;

- blockage of the pipes due to coarsening of the grinding, introduction of foreign objects and gaps in the closed facilities;

- bursting of fittings or other accidents caused by freezing;

- knocking out of seals in the pump units, stopping the water for hydro-sealing the pumps;

- breaks in the electrical network in the starting and protective equipment of the electrical units and other accidents in the electrical systems.

2. On the main and alluvial wall:

- deformations due to subsidence of the terrain and the body of the walls;

- uncontrolled filtration, through the main alluvial wall or the main terrain, accompanied by or without undermining;

- erosion of the slopes of the alluvial and main wall during catastrophic rainfall, snowmelt and breaches in the tailings pipes;

- collapse of the slopes in the main and alluvial wall due to leaks or deformation of the collectors, regulators or when karst phenomena occur in the base;

- rupture of the walls of the tailings ponds during earthquakes, when water overflows through the crown of the wall and when clogging of the water intake facilities and collectors and a rise in the water level until it overflows through the crown of the wall;

- compromising the facilities for protection against external waters. When external waters enter the sediment lake, the level rises and can cause overflow through the crown of the wall.

3. Fires in the buildings and facilities of the tailings pond as a result of non-compliance with fire safety measures or as a result of natural disasters.

4. Malicious acts.

References:

1. Belokonski, I., Preventive activities and scientific support for the protection of the population in the event of disasters and accidents. Proceedings of a scientific and practical conference on the protection of the population in the event of disasters and accidents, 1992.
2. Directive 2006/21/EC
3. Law on Subsoil Resources (Official Gazette, No. 23 of March 12, 1999).
4. Law on Spatial Planning (Official Gazette, No. 1 of January 2, 2001).
5. ECE Convention
6. Explanatory Dictionary of the Modern Bulgarian Language.

7. Recommendations for the Design of Tailings Reservoirs in Harsh Climate Conditions.
8. http://stroiteli.elmedia.net/sti/bg/20173/editorials/%D0%B8%D0%B7%D0%B3%D1%80%D0%B0%D0%B6%D0%B4%D0%B0%D0%BD%D0%B5-%D0%BD%D0%B0-%D1%85%D0%B2%D0%BE%D1%81%D1%82%D0%BE%D1%85%D1%80%D0%B0%D0%BD%D0%B8%D0%BB%D0%B8%D1%89%D0%B0_04703.html.
9. https://www.moew.government.bg/bg/regionalnite-inspekcii-po-okolnata-sreda-i-vodite-izvurshvat-ejegodni-proverki-za-pravilnata-eksploataciya-na-obsto-12-te-dejstvasti-hvostohranilista-na-teritoriyata-na-stranata/

ДИГИТАЛИЗАЦИЯ И ВЗАИМОДЕЙСТВИЕ ЧОВЕК-МАШИНА: ПСИХОЛОГИЧЕСКИ ФАКТОРИ ЗА ПРИЕМАНЕ НА ИНТЕЛИГЕНТНИ СИСТЕМИ В УСТОЙЧИВОТО ОБЩЕСТВО[1]

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DIGITALIZATION AND HUMAN–MACHINE INTERACTION: PSYCHOLOGICAL FACTORS INFLUENCING THE ACCEPTANCE OF INTELLIGENT SYSTEMS IN A SUSTAINABLE SOCIETY

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Paisii Hilendarski University of Plovdiv

Abstract: *The paper examines future psychologists' attitudes toward the implementation of artificial intelligence and intelligent systems in psychological practice by 2030. The empirical study was conducted online in 2025 among 73 psychology students using an author-designed questionnaire with 10 prognostic statements assessed on a 5-point Likert scale. The results indicate cautious optimism and a predominantly moderate assessment of the likelihood of AI integration into professional practice. The highest confidence was expressed regarding awareness-raising and educational initiatives, as*

[1] *Настоящото изследване е разработено в рамките на научния проект „Психология на взаимодействието човек–машина: Мултимодални подходи за социалнопсихологическа диагностика с интеграция на изкуствен интелект и интелигентни системи“ (ИНСАЙТ), финансиран по Фонд „Научни изследвания“, договор № КП-06-Н-65/8, ръководител проф. М. Митевска*

well as the use of AI tools in psychodiagnostic assessment. The findings highlight the need for increased awareness, digital competence development, and a human-centred approach.

Keywords: *artificial intelligence, intelligent systems, psychological practice, psychology students, digital transformation*

В съвременния контекст на дигитализация изкуственият интелект все по-често се разглежда като инструмент за подпомагане на психодиагностиката, анализа на данни, скрининга и проследяването на психичното състояние (D'Alfonso, 2020; Graham et al., 2019). Въпреки това интелигентните технологии не следва да заменят психолога, а да подпомагат професионалната му дейност при запазване на етичната отговорност, прозрачността и човешкия контрол (Luxton, 2014; Miner et al., 2019).

Актуалността на темата се определя от нарастващото внимание на международни организации към отговорното и човекоцентрично използване на ИИ в здравеопазването и психологическата практика. Световната здравна организация подчертава потенциала на ИИ за подобряване на здравните услуги, но и необходимостта от защита на човешките права, сигурността и отчетността (World Health Organization, 2021). Подобна позиция застъпва и Американската психологическа асоциация, която акцентира върху нуждата психолозите да развиват компетентности за критично и етично използване на ИИ инструменти (American Psychological Association, 2024, 2025). В европейски контекст темата се свързва и с регулаторните изисквания за управление на риска, прозрачност и човешки надзор при използване на ИИ системи (European Commission, 2024).

Особено значение има изследването на нагласите на бъдещите психолози, тъй като те ще бъдат сред активните участници в професионална среда, в която интелигентните технологии ще намират все по-широко приложение. Според моделите за приемане на технологии възприеманата полезност, леснотата на използване, социалното влияние и наличието на подкрепящи условия са ключови фактори за готовността за използване на нови технологични решения (Venkatesh et al., 2003).

Настоящото изследване разглежда нагласите, очакванията и възприеманата вероятност за внедряване на ИИ и интелигентни

системи в психологическата практика до 2030 г. сред студенти по психология. Целта е да се проучи как бъдещите специалисти оценяват възможностите за приложение на тези технологии и как ги свързват с променящата се професионална роля на психолога. Основните задачи са да се установи самооценъчното ниво на познания относно ИИ, да се анализират очакванията за приложението му в различни обществени и професионални сфери и да се очертае общият профил на нагласите към интеграцията му в психичното здраве.

Обект на изследването е процесът на интегриране на ИИ и интелигентни системи в психологическата практика, а предмет — нагласите и очакванията на студентите по психология към това внедряване. Емпиричният обхват включва 73 студенти от бакалавърска степен в държавен университет в България. Основната хипотеза е, че участниците ще оценяват внедряването на ИИ като умерено вероятно и ще проявяват предпазлив оптимизъм, без крайна поляризация. Допуска се също, че по-високото самооценъчно ниво на познания за ИИ ще бъде свързано с по-положителни очаквания, а най-висока увереност ще се наблюдава по отношение на информационните кампании и използването на ИИ инструменти в психодиагностиката.

Изследването има теоретична и практическа значимост, тъй като допринася за по-доброто разбиране на нагласите към ИИ в психологическата професия и подчертава необходимостта от адаптиране на университетското обучение към изискванията на дигиталната среда. Успешното внедряване на интелигентни системи изисква не само технологичен напредък, но и доверие, информираност, дигитални компетентности и човекоцентричен подход, при който водеща остава професионалната роля на психолога.

Теоретични постановки

Теоретичната основа на настоящото изследване обединява подходи, свързани с приемането на технологии, взаимодействието човек–машина, доверието в автоматизацията, човекоцентричния изкуствен интелект и приложението на ИИ в психичното здраве. Тези направления позволяват да се анализират не само възможностите на интелигентните системи, но и психологическите фактори, които влияят върху тяхното възприемане и използване в професионалната практика.

Една от основните рамки е Моделът за приемане на технологии на Davis (1989), според който намерението за използване на дадена технология зависи най-вече от възприеманата полезност и лекота на използване. В контекста на психологическата практика това означава, че приемането на ИИ инструменти е свързано с оценката на тяхната приложимост, надеждност и практическа стойност. Тази перспектива се разширява от Venkatesh et al. (2003), които подчертават ролята на очакваната ефективност, социалното влияние и подкрепящите условия за използване на нови технологии.

Изследванията върху взаимодействието човек–машина показват, че автоматизацията не замества напълно човешката дейност, а променя начина на вземане на решения и упражняване на контрол (Parasuraman et al., 2000). Това е особено важно в психологията, където професионалната преценка, емпатията и етичната отговорност не могат да бъдат изцяло делегирани на алгоритми. В тази връзка доверието в автоматизацията е ключов фактор за използването на интелигентни системи. Lee и See (2004) подчертават, че доверието трябва да бъде съобразено с реалните възможности и ограничения на технологията, тъй като както недоверието, така и прекомерното доверие могат да доведат до неефективна или рискова употреба.

Значима теоретична основа е и човекоцентричният подход към ИИ. Според Shneiderman (2020) интелигентните системи трябва да подпомагат човешките способности, а не да ги изместват, като съчетават автоматизация с човешки контрол. Подобна позиция е застъпена и в ISO 9241-210:2019, където човекоцентричното проектиране се свързва със създаването на полезни и използваеми системи, съобразени с потребностите на потребителите. В сферата на психичното здраве това е особено важно поради чувствителността на личните данни, необходимостта от конфиденциалност и високата професионална отговорност.

ИИ има потенциал да подпомага ранното откриване на проблеми, персонализирането на интервенции, анализа на големи масиви от данни и разширяването на достъпа до услуги в психичното здраве (Graham et al., 2019; D'Alfonso, 2020). В същото време приложението му е свързано с рискове като алгоритмични пристрастия, липса на прозрачност, ограничена обяснимост и опасност от редуциране на сложни психологически процеси до количествени показатели. Затова интелигентните системи следва да имат подпомагаща, а не заместваща роля, съобразена с

етичните стандарти и професионалната отговорност на психолога.

Допълнителна перспектива дават изследванията върху афективните изчисления и мултимодалната оценка на човешките реакции. Picard (1997) разглежда емоциите като съществен елемент от взаимодействието с технологиите, а съвременните подходи за анализ на емоционални реакции, биометрични показатели и проследяване на погледа позволяват по-задълбочено разбиране на потребителското преживяване (Calvo & D'Mello, 2010; Duchowski, 2017). В по-широк социален план теорията за дифузията на иновациите показва, че приемането на нови технологии зависи от тяхната полезност, съвместимост със съществуващите ценности, лесната на използване и видимост на резултатите (Rogers, 2003).

Нормативно-етичният контекст също е съществен. Световната здравна организация подчертава, че използването на ИИ в здравеопазването трябва да се основава на човешка автономия, прозрачност, отчетност, справедливост и устойчивост (World Health Organization, 2021). Европейският акт за изкуствения интелект също акцентира върху отговорното разработване и внедряване на ИИ системи, особено когато те могат да засегнат здравето, безопасността и основните права на хората (European Commission, 2024).

В обобщение, интеграцията на интелигентни системи в психологическата практика следва да се разглежда като технологичен, психологически, социален, етичен и образователен процес. Приемането на ИИ зависи от възприеманата му полезност, доверието, прозрачността, професионалната подкрепа и съответствието с ценностите на психологическата професия. Затова нагласите на студентите по психология са важен индикатор за бъдещото развитие на професията в условията на дигитална трансформация.

Методология

Емпиричното изследване е реализирано онлайн през 2025 г. чрез платформата Google Forms и се основава на специално разработен авторски въпросник, включващ 10 прогностични твърдения. Те обхващат основни сфери на приложение на интелигентни технологии в психологическата практика — политика, общество, индустрия, образование и професионална дейност — като всяка

област е представена с по две прогнози. Анализът е насочен към оценка на средносрочното въздействие на тези технологии, при хоризонт до 2030 г., чрез използване на Ликертова скала, вариращa от 1- изобщо не е вероятно до 5 – силно вероятно. Конструирането на инструмента е базирано на задълбочен преглед на научната литература и експертна оценка, с цел гарантиране на съдържателна валидност. Проучването е анонимно и включва събиране на ограничен набор от демографски данни — възраст, пол и и самооценъчно ниво на познания в областта на изкуствения интелект. Извадката включва 73 студенти по психология (бакалавърска степен) от държавен университет в България. Макар ограниченият ѝ обхват да предполага предпазливост при обобщаване на резултатите, получените данни предоставят ценен поглед върху нагласите на бъдещи специалисти към интеграцията на интелигентни технологии. В този контекст се откроява значението на психологическите фактори при приемането на технологиите и необходимостта от адаптиране на професионалното обучение към изискванията на дигиталната среда.

Анализ на резултатите

Тъй като фокусът на настоящото изследване е свързан с изкуствения интелект (ИИ) и интелигентните системи, беше оценено нивото на запознатост с ИИ. Въпреки че респондентите са студенти по психология, почти половината от тях (48.2 %) притежават средно ниво на познания в областта на ИИ. 37.5 % участници имат базово ниво на запознатост, а 14.3 % се самоопределят като напреднали в тези технологии. Резултатите са представени в кръговата диаграма по-долу.



Фигура 1. Ниво на познание в изкуствен интелект

По отношение на демографските характеристики, повечето студенти попадат във възрастовата група 18–24 години (91%). 3.6% от участниците са на възраст 25–34 години, както и в диапазона 35-44 години. 1.8% от респондентите са на възраст между 45–54 години. Що се отнася до пола, 79% са представителите от женски пол и 21% са участниците от мъжки пол. Резултатите са визуализирани на фигури 2 и 3.



Фигура 2. Разпределение на участниците по възрастови групи



Фигура 3. Разпределение на участниците по пол

За да се провери очакваната вероятност на реализация на сценариите, посочени в съответните твърдения, бе проверена средната стойност от 5-степенната скала по Ликерт за всяко твърдение. Целта бе да се установи дали възгледите на респондентите са сходни. Резултатите бяха обработени чрез Python библиотеки и са представени на Фигура 4.



Фигура 4. Очаквана вероятност- средна стойност по твърдение

Като цяло, всички средни стойности се намират в диапазона приблизително между около 3, съответстващо на „умерено вероятно“ по пет 5-степенната скала. Това означава, че участниците проявяват по-скоро предпазлив оптимизъм относно бъдещото реализацията на посочените сценарии до 2030 г.

Най-висока средна стойност имат твърдение 4 и твърдение 8 - над 3, което предполага, че те се възприемат като най-вероятни от респондентите. Твърдение 4 гласи „До 2030 г. в страната ще бъдат проведени национални кампании и образователни програми за повишаване на обществената осведоменост относно използването на изкуствен интелект и роботизирани технологии в психичното здраве, като поне 70% от психолозите и 50% от населението ще бъдат информирани чрез медийни и обучителни инициативи“, а твърдение 8 – „До 2030 г. подпомогнати от изкуствен интелект инструменти за психодиагностична оценка (включително тестове и въпросници) ще бъдат интегрирани в практиката на поне 50% от психолозите и клиничните центрове в страната“. От една страна респондентите очакват значително институционално и обществено усилие за повишаване на информираността относно ИИ и роботизираните технологии в психичното здраве. Това предполага доверие в ролята на образованието, медиите и публичните политики като двигатели на дигиталната трансформация. От друга страна, респондентите очакват реална и практическа интеграция на ИИ инструменти в професионалната дейност на психолозите. Това показва, че участниците не възприемат интелигентните технологии само на теоретично или информационно ниво, а като конкретен инструмент, който ще стане част от ежедневната практика.

Останалите твърдения се групират около средната стойност 3, което означава умерена вероятност според участниците.

В обобщение, резултатите показват липса на краен оптимизъм или песимизъм, а по-скоро балансирано, умерено възприемане на възможностите за интеграция на интелигентни технологии, с известни различия между отделните аспекти. Респондентите проявяват най-висока увереност именно в процесите на информиране и практическо внедряване на интелигентни технологии. Това очертава тенденция към постепенно нормализиране на ИИ в психологията, подкрепено както от обществени инициативи, така и от професионално приложение.

Беше проверено и общото разпределение на отговорите по 5-степенната Ликертова скала с цел да се установи преобладаващата тенденция в оценките и да се идентифицира общият профил на нагласите на участниците. Резултатите са показани на Фигура 5.



Фигура 5. Разпределение на вариантите на Ликертовата скала на база 10-те твърдения

Общото разпределение на отговорите по 5-степенната Ликерт скала показва ясно изразена концентрация около отговор „Умерено вероятно“ (31.4%), което свидетелства за преобладаващо неутрално или умерено ниво на оптимизъм на участниците. Същевременно крайните отговори – „Изобщо не е вероятно“, съответстващо на 1 и „Силно вероятно“, съответстващо на 5 са с почти еднакъв процент – 10% и 10.4% респективно, като тези проценти са най-ниски по отношение на отговори. Това показва липса на ясно доминираща позиция и отсъствие на силна

поляризация. Почти еднакъв процент наблюдаваме и при отговори „Слабо вероятно“ (2) и „Много вероятно“(4) – 24% и 24.2%. Това отново потвърждава балансирано разпределение на мненията, без ясно изразено предпочитание към по-скоро положителна или по-скоро отрицателна посока сред респондентите. В обобщение липсата на концентрация в крайни оценки и преобладаване на умерена вероятност показват известна степен на несигурност в оценките.

Дискусия

Получените резултати очертават предпазлив, но неотхвърлящ подход към интеграцията на интелигентни системи в психичното здраве. Доминирането на средни стойности около „умерено вероятно“ и липсата на концентрация в крайните категории показват, че участниците не заемат крайни позиции, а оценяват бъдещото приложение на ИИ с умерена увереност и известна несигурност. Това потвърждава първата хипотеза, че внедряването на ИИ в психологическата практика ще бъде възприемано като умерено вероятно, както и четвъртата хипотеза, според която нагласите на студентите се характеризират с предпазлив оптимизъм.

Най-високи стойности са отчетени при твърденията, свързани с повишаване на информираността и практическото внедряване на ИИ инструменти в психодиагностиката. Това потвърждава третата хипотеза и показва, че участниците възприемат образованието, публичната информираност и професионалното приложение като най-реалистични посоки за развитие до 2030 г.

Втората хипотеза, свързана с очакването участниците с по-високо ниво на познания за ИИ да проявяват по-положителни нагласи, може да се приеме като частично потвърдена, тъй като данните показват преобладаващо средно ниво на информираност, но за по-категоричен извод е необходим допълнителен статистически анализ.

В обобщение, резултатите показват, че нагласите на студентите все още се формират и зависят от фактори като прозрачност, надеждност, етичност и човешки контрол върху технологиите. Това подкрепя значението на човекоцентричния подход при разработването и внедряването на интелигентни системи. Липсата на силна поляризация показва потенциал за положително развитие на нагласите, ако бъде осигурена

достатъчна информираност, професионална подготовка и яснота относно възможностите и ограниченията на ИИ.

Заключение

Настоящото изследване показва, че участниците възприемат интеграцията на интелигентни технологии в психичното здраве като умерено вероятна, като нагласите им се характеризират с предпазлив оптимизъм и известна несигурност. Липсата на крайни оценки и балансираното разпределение на мненията свидетелстват за отсъствие на силна поляризация, но и за все още неустойчиво формирано отношение към тези технологии. Най-висока степен на увереност се наблюдава по отношение на повишаването на информираността и практическата интеграция на интелигентни системи, което подчертава значението на образованието, институционалната подкрепа и професионалното приложение като ключови фактори за бъдещото им развитие.

В обобщение, резултатите сочат, че успешното внедряване на интелигентни системи изисква не само технологичен напредък, но и целенасочени усилия за изграждане на доверие, повишаване на ангажираността и формиране на позитивно възприятие сред потребителите. В този процес човекоцентричният подход се явява основополагащ за устойчивото и ефективно интегриране на интелигентните технологии в практиката.

Литература:

1. American Psychological Association. (2024). Artificial intelligence and the field of psychology.
2. American Psychological Association. (2025). Ethical guidance for AI in the professional practice of health service psychology.
3. Calvo, R. A., & D'Mello, S. (2010). Affect detection: An interdisciplinary review of models, methods, and their applications. IEEE Transactions on Affective Computing, 1(1), 18–37. doi:10.1109/T-AFFC.2010.1
4. D'Alfonso, S. (2020). AI in mental health. Current Opinion in Psychology, 36, 112–117. doi:10.1016/j.copsyc.2020.04.005
5. Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319–340. doi:10.2307/249008
6. Duchowski, A. T. (2017). Eye tracking methodology: Theory and practice (3rd ed.). Springer. doi:10.1007/978-3-319-57883-5
7. European Commission. (2024). AI Act enters into force.

8. Graham, S., Depp, C., Lee, E. E., Nebeker, C., Tu, X., Kim, H. C., & Jeste, D. V. (2019). Artificial intelligence for mental health and mental illnesses: An overview. Current Psychiatry Reports, 21, Article 116. doi:10.1007/s11920-019-1094-0
9. International Organization for Standardization. (2019). ISO 9241-210:2019 Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems. ISO.
10. Lee, J. D., & See, K. A. (2004). Trust in automation: Designing for appropriate reliance. Human Factors, 46(1), 50–80. doi:10.1518/hfes.46.1.50_30392
11. Luxton, D. D. (2014). Recommendations for the ethical use and design of artificial intelligent care providers. Artificial Intelligence in Medicine, 62(1), 1–10. doi:10.1016/j.artmed.2014.06.004
12. Miner, A. S., Milstein, A., & Hancock, J. T. (2017). Talking to machines about personal mental health problems. JAMA, 318(13), 1217–1218. doi:10.1001/jama.2017.14151
13. Miner, A. S., Shah, N., Bullock, K. D., Arnow, B. A., Bailenson, J., & Hancock, J. T. (2019). Key considerations for incorporating conversational AI in psychotherapy. Frontiers in Psychiatry, 10, Article 746. doi:10.3389/fpsyt.2019.00746
14. Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. IEEE Transactions on Systems, Man, and Cybernetics — Part A: Systems and Humans, 30(3), 286–297. doi:10.1109/3468.844354
15. Picard, R. W. (1997). Affective computing. MIT Press.
16. Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.
17. Shneiderman, B. (2020). Human-centered artificial intelligence: Reliable, safe & trustworthy. International Journal of Human–Computer Interaction, 36(6), 495–504. doi:10.1080/10447318.2020.1741118
18. Torous, J., & Roberts, L. W. (2017). Needed innovation in digital health and smartphone applications for mental health: Transparency and trust. JAMA Psychiatry, 74(5), 437–438. doi:10.1001/jamapsychiatry.2017.0262
19. Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. MIS Quarterly, 27(3), 425–478. doi:10.2307/30036540
20. World Health Organization. (2021). Ethics and governance of artificial intelligence for health: WHO guidance. World Health Organization.

ПРЕДИМСТВА НА ФОТОВОЛТАИЧНИТЕ ЗАРЯДНИ СТАНЦИИ ЗА ЕЛЕКТРИЧЕСКИТЕ ПРЕВОЗНИ СРЕДСТВА

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ADVANTAGES OF PHOTOVOLTAIC CHARGING STATIONS FOR ELECTRIC VEHICLES

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Abstract: *Solar-powered charging stations for electric vehicles (EVs) combine solar photovoltaic (PV) systems, using solar energy to charge electric vehicles. This approach reduces the consumption of fossil fuels and limits greenhouse gas emissions, thereby contributing to a cleaner environment. With an average of 240 sunny days per year, the country has significant potential for harnessing solar energy. An additional factor in realizing this potential is the current policy and incentives in the field of renewable energy.*

Keywords: *Electric vehicles, charging infrastructure, photovoltaic charging stations*

Според статистически данни слънчевото греене в България, което представлява максимално възможната стойност за географската ширина на страната, е приблизително 4400–4500 часа годишно. Поради наличието на облачност реалната продължителност на слънчевото греене е около 50% от тази стойност – между 2100 и 2500 часа годишно. Това прави страната подходяща за инсталиране и инвестиране във фотоволтаични зарядни станции.



След първоначалната инвестиция в слънчеви панели и тяхното изграждане, текущите оперативни разходи са сравнително ниски. Слънчевата енергия е безплатен ресурс, а разходите за поддръжка са значително по-ниски в сравнение с традиционните енергийни източници. Това икономическо предимство прави зарядните станции, захранвани със слънчева енергия, привлекателна опция както за публични, така и за частни инвестиции.

Икономическите ползи от зарядните станции за електрически превозни средства, захранвани със слънчева енергия, са многопластови и включват по-ниска цена на единица енергия, както и значителни спестявания за потребителите.

- **Стабилност и предвидимост:** Слънчевата енергия осигурява относително стабилни и предвидими разходи за електроенергия, като по този начин защитава потребителите от ценовата волатилност на електроенергията от мрежата. Това води до по-предсказуеми и управляеми енергийни разходи за домакинствата.
- **Спестявания от поддръжка:** Системите, базирани на слънчева енергия, имат значително по-ниски изисквания за поддръжка в сравнение със сложната инфраструктура на конвенционалните електроцентрали. Това намалява индиректните разходи, свързани със зареждането на електрически превозни средства.
- **Увеличено използване на електрически превозни средства:** Намалените разходи за зареждане водят до по-ниска обща цена на притежание на електромобил, което ги прави по-конкурентоспособни спрямо превозните средства с двигатели с вътрешно горене (ICE). Това може да ускори тяхното навлизане на пазара и да доведе до по-широки икономически и обществени ползи, включително намалени разходи за здравеопазване вследствие на по-ниско замърсяване на въздуха.

Въздействието върху околната среда на зарядните станции за електрически превозни средства, захранвани със слънчева енергия, е изключително положително. Те допринасят за значително намаляване на въглеродните емисии, ограничаване на зависимостта от изкопаеми горива, подобряване на качеството на въздуха и насърчаване на устойчивото използване на енергийни ресурси.

Едно от най-съществените екологични предимства на слънчево захранваните зарядни станции е редукцията на въглеродните

емисии и потреблението на изкопаеми горива. Традиционното производство на електроенергия, особено чрез въглища и природен газ, е основен източник на въглероден диоксид (CO_2), който допринася за глобалното затопляне и климатичните промени. Използването на слънчева енергия като алтернативен източник значително намалява този негативен ефект върху околната среда.

• **Нулеви емисии по време на работа:** Слънчевите панели генерират електрическа енергия без отделяне на въглероден диоксид (CO_2) или други парникови газове по време на експлоатацията си. Използването на слънчева енергия за зареждане на електрически превозни средства позволява значително намаляване на въглеродния отпечатък в транспортния сектор.

• **Емисии през жизнения цикъл:** Въпреки че при производството, транспортирането и монтажа на слънчеви панели се генерират емисии, те са значително по-ниски в сравнение с емисиите, свързани с електроцентрали, работещи с изкопаеми горива. В дългосрочен план слънчевите панели произвеждат многократно по-малко CO_2 на kWh произведена електроенергия.

• **Кумулативно въздействие:** С увеличаването на броя на слънчево захранваните зарядни станции за електрически превозни средства, общият ефект върху намаляването на въглеродните емисии става значителен. Това подпомага изпълнението на национални и международни климатични цели, включително ангажиментите по Парижкото споразумение.

• **Диверсификация на енергийните източници:** Слънчевата енергия представлява възобновяем и практически неизчерпаем ресурс, който намалява зависимостта от въглища, нефт и природен газ. Това допринася за по-висока енергийна сигурност и по-ниска чувствителност към ценови колебания и прекъсвания в доставките.

• **Намаляване на добива на изкопаеми горива:** По-ниската зависимост от изкопаеми горива води до ограничаване на дейности като добив и преработка, които имат сериозно негативно въздействие върху околната среда, включително разрушаване на екосистеми и замърсяване на води и почви.

• **Енергийна независимост:** Използването на слънчева енергия допринася за по-голяма енергийна автономност на държавите, като намалява зависимостта от внос на изкопаеми горива и

съответно редуцира геополитическите и икономическите рискове, свързани с енергийните доставки.

Зарядните станции за електрически превозни средства, захранвани със слънчева енергия, предлагат редица предимства по отношение на разположението и достъпността, особено в отдалечени и селски райони. Те представляват практично и мащабируемо решение за места с ограничен или липсващ достъп до електроенергийната мрежа, като същевременно повишават енергийната независимост и намаляват разходите, свързани с изграждането на традиционна инфраструктура.

Тези системи осигуряват надежден и устойчив източник на енергия в райони, където конвенционалната електрическа инфраструктура е недостатъчно развита или икономически неоправдана.

- ***Географска гъвкавост:*** Слънчевите панели могат да бъдат инсталирани в широк спектър от локации – от градски центрове до отдалечени селски райони. Те не изискват близост до електроцентрали или сложна преносна мрежа, което ги прави особено подходящи за райони с ограничен достъп до електрическата мрежа.
- ***Мащабируемост:*** Слънчевите енергийни системи могат лесно да бъдат адаптирани според конкретните енергийни нужди. Малки локални инсталации могат да обслужват отделни общности или населени места, докато по-големи системи могат да захранват множество зарядни станции и да покриват по-широки енергийни потребности.
- ***Лесната на инсталиране:*** Модулният характер на слънчевите панели и зарядните станции позволява относително бързо и лесно изграждане. Това е особено важно в отдалечени райони, където разгръщането на традиционна електроенергийна инфраструктура би било сложно, бавно и финансово натоварващо.

В райони без електрозахранване от мрежата или с ненадеждна електрическа инфраструктура, зарядните станции за електрически превозни средства, захранвани със слънчева енергия, представляват ключова алтернатива за осигуряване на устойчива мобилност.

- ***Енергийна независимост:*** Слънчево захранваните станции произвеждат собствена електроенергия, което намалява зависимостта от нестабилни или липсващи електроразпределителни мрежи. Това е особено важно в региони с чести прекъсвания на

електрозахранването, като осигурява непрекъсната възможност за зареждане на електрически превозни средства.

- ***Решения извън мрежата:*** В напълно автономни (off-grid) райони слънчевите зарядни станции могат да функционират независимо от централизираната електроенергийна система. Това ги прави жизнеспособно решение за места, където изграждането на традиционна инфраструктура е технически или икономически неприложимо, и същевременно подпомага разширяването на електрическата мобилност.
- ***Спестяване на разходи:*** Изграждането на електроразпределителна мрежа в отдалечени райони е свързано с високи инвестиционни разходи. Слънчевите решения значително намаляват тези разходи, като предоставят по-достъпна алтернатива за внедряване на зарядна инфраструктура. Това позволява по-бързо развитие на услуги в слабо обслужвани региони и ускорява разпространението на електрическите превозни средства.

Подкрепа за приемането на електрически превозни средства в селските райони

Зарядните станции за електрически превозни средства, захранвани със слънчева енергия, могат значително да подпомогнат внедряването и използването на електромобили в селските райони, които често се сблъскват със специфични инфраструктурни и икономически предизвикателства.

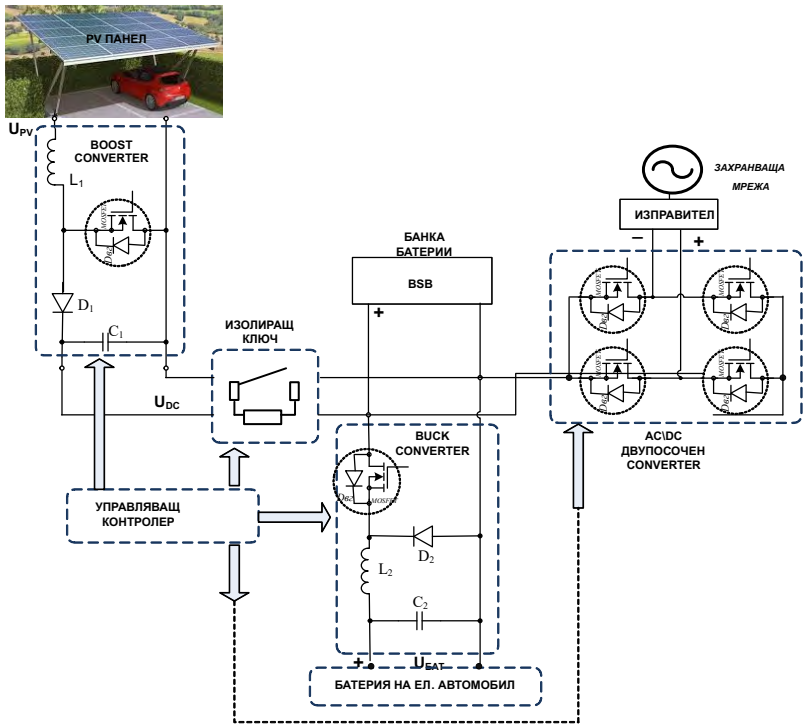
- ***Достъп до чиста енергия:*** Селските региони получават възможност да използват чиста и възобновяема енергия за зареждане на електрически превозни средства, което допринася за намаляване на въглеродните емисии и насърчава екологичната устойчивост. Това е в съответствие с по-широките стратегии за устойчиво развитие и внедряване на зелени енергийни решения.
- ***Икономически ползи:*** Изграждането и експлоатацията на слънчево захранвана зарядна инфраструктура може да стимулира местната икономика чрез създаване на нови работни места в областта на инсталацията, поддръжката и управлението на системите. Освен това, по-ниските разходи за енергия и зареждане осигуряват значително финансово облекчение за собствениците на електрически превозни средства в селските райони.
- ***Подобряване на мобилността:*** Достъпът до надеждни зарядни станции за електрически превозни средства може значително да подобри мобилността в селските райони, като

позволява на жителите да пътуват на по-дълги разстояния без притеснение от изчерпване на батерията. Това от своя страна улеснява достъпа до образование, здравни услуги и икономически възможности.

- ***Правителствена подкрепа и стимули:*** Много държави прилагат различни стимули и субсидии за насърчаване на използването на възобновяема енергия и електрически превозни средства, особено в по-слабо развитите и селските региони. Слънчево захранваните зарядни станции могат да се възползват от подобни програми, което ги прави по-икономически изгодни и привлекателни за местните общности.
- ***Намаляване на зависимостта от горива:*** В много селски райони транспортът все още е силно зависим от бензин и дизел, които са свързани с високи разходи и негативно въздействие върху околната среда. Слънчево захранваните зарядни станции за електрически превозни средства предлагат устойчива алтернатива, като намаляват зависимостта от изкопаеми горива и повишават енергийната независимост и сигурност.

Изграждането на зарядни станции за електрически превозни средства, захранвани от слънчева енергия, е свързано с редица значими предизвикателства. Сред основните пречки са високите първоначални инвестиционни разходи, необходимостта от държавни стимули и субсидии, както и недостатъчната стандартизация на зарядните конектори и инфраструктурата.

Интегрирането на слънчевата енергия в инфраструктурата за зареждане на електрически превозни средства е особено перспективно, тъй като свързва производството на чиста енергия директно с крайното потребление. Въпреки това съществуват редица технически бариери, по-специално в областта на силовата електроника, съвместимостта с електроразпределителната мрежа и системите за управление на енергията. Освен това, неефективното управление на енергийните потоци може да съкрати експлоатационния живот на батериите или да влоши производителността на електрическите превозни средства.



Фиг. 1. Блокова схема на PV зарядна станция

Усъвършенстваните системи за управление на енергията, включващи прогнозно моделиране, адаптация в реално време и интеграция на системи за съхранение, са от съществено значение за осигуряване на ефективно зареждане на електрически превозни средства, захранвани със слънчева енергия.

Едно от най-съществените предизвикателства при изграждането на зарядни станции за електрически превозни средства, захранвани със слънчева енергия, са високите първоначални инвестиционни разходи.

• **Слънчеви панели и оборудване:** Разходите за закупуване и инсталиране на фотоволтаични панели, инвертори, батерийни системи и съпътстващо оборудване са значителни. Високоефективните панели, макар и с по-висока производителност, се характеризират и с по-висока цена.

• **Инфраструктура за зареждане:** Изграждането на зарядни станции за електрически превозни средства изисква съществени инвестиции в зарядно оборудване, като разходите зависят от типа и мощността на зарядните устройства (ниво 1, ниво 2 или бързи DC зарядни станции).

• **Подготовка и монтаж на обекта:** Подготовката на площадката, включително строително-монтажни дейности, електрическо окабеляване и монтаж на конструкции, съществено увеличава общите разходи. Допълнително значим дял имат трудовите и инженерните услуги.

• **Системи за съхранение на енергия:** За осигуряване на непрекъснато електрозахранване, особено при ниска слънчева радиация или през нощта, са необходими инвестиции в батерийни системи за съхранение. Те представляват ключов, но и разходоемък компонент, в зависимост от капацитета и използваната технология.

Инвестиционни изисквания за слънчеви панели и инфраструктура

Инвестирането в зарядна инфраструктура за електрически превозни средства, захранвана със слънчева енергия, изисква значителен капитал, което може да представлява бариера за редица заинтересовани страни.

• **Капиталоемкост:** Високите капиталови разходи, свързани със слънчеви фотоволтаични системи, зарядна инфраструктура и системи за съхранение на енергия, могат да възпрат потенциални инвеститори. Осигуряването на финансиране от финансови институции често е затруднено поради възприемания риск и дългите периоди на възвръщаемост.

• **Възвръщаемост на инвестициите:** Инвеститорите обикновено изискват ясна и конкурентна възвръщаемост, която да оправдае високите първоначални разходи. Продължителните периоди на изплащане при слънчеви енергийни проекти могат да представляват предизвикателство, особено на пазари с нестабилни цени на енергията или несигурна регулаторна рамка.

Липса на стандартизация в зарядните конектори и инфраструктурата

Липсата на стандартизация в зарядните конектори и свързаната инфраструктура представлява съществено техническо и логистично предизвикателство при внедряването на зарядни станции за електрически превозни средства, захранвани със слънчева енергия.

• **Разнообразие от стандарти:** В различните региони и при различни производители се използват несъвместими стандарти за зареждане, като CHAdeMO, CCS (Combined Charging System) и

собствени решения като тези на Tesla. Това разнообразие затруднява оперативната съвместимост и усложнява изграждането на унифицирана инфраструктура.

• **Проблеми със съвместимостта:** Несъвместимостта между превозните средства и наличните зарядни станции може да ограничи достъпа на потребителите до инфраструктурата, което води до неудобства и възпрепятства по-широкото навлизане на електромобилите.

• **Интеграция на инфраструктурата:** Интегрирането на слънчево захранвани зарядни станции със съществуващите електроразпределителни системи е комплексен процес. Той включва предизвикателства, свързани със свързаността към мрежата, управлението на енергийни потоци и координацията между фотоволтаични системи и системи за съхранение на енергия.

• **Необходимост от универсални стандарти:** Разработването и прилагането на унифицирани стандарти за зареждане на електрически превозни средства би улеснило внедряването на инфраструктурата, би подобрило оперативната съвместимост и би повишило ефективността на системата като цяло.

Регулаторна рамка – Европейски съюз: В рамките на Европейския съюз инициативи като Европейския зелен пакт (Green Deal) поставят цели за увеличаване дела на възобновяемите енергийни източници и намаляване на въглеродните емисии. Европейската комисия насърчава развитието на инфраструктура за алтернативни горива, включително зарядни станции за електрически превозни средства, чрез общи технически и регулаторни насоки за държавите членки.

Изводи

1. Зарядните станции за електрически превозни средства, захранвани със слънчева енергия, предоставят съществени икономически, екологични и социални ползи, включително намаляване на оперативните разходи, емисиите на парникови газове и зависимостта от изкопаеми горива.
2. Тяхното внедряване допринася за създаване на нови работни места и стимулиране на местното икономическо развитие.
3. Въпреки съществуващите предизвикателства, като високите първоначални инвестиционни разходи и липсата на стандартизация, тези системи притежават значителен

потенциал за устойчиво развитие и технологичен напредък в областта на чистата енергия.

Бързото нарастване на използването на електрически превозни средства води до повишено търсене на зарядни станции, захранвани със слънчева енергия. Това развитие трябва да отговори на нарастващото потребление. Очаква се слънчево захранваните зарядни станции да играят ключова роля, особено в селските и отдалечени райони, където достъпът до електроразпределителната мрежа е ограничен.

Литература:

1. https://pulseenergy.io/blog/ev-charging-station-design
2. https://uta.pressbooks.pub/sustainablemobility/chapter/chapter-7-design-of-charging-infrastructure/
3. https://www.kviconline.gov.in/pmegp/pmegpweb/docs/commonprojectprofile/EVChargingStation.pdf
4. https://upcommons.upc.edu/server/api/core/bitstreams/114d6dcd-a098-4930-a380-7267ab29982f/content
5. https://www.researchgate.net/figure/Architecture-of-conventional-EV-charging-station-a-Common-AC-bus-based-system-and-b_fig2_370036926
6. https://www.sciencedirect.com/topics/engineering/ev-charging-station
7. Радостин Долчинков, Камен Сейменлийски, Иван Попов, Безопастност на електрически автомобил. Сборник с доклади от Международна научна конференция „Черно море - Врата и много мостове“, 2022, Бургас, изд. БСУ,, ISBN: 978-619-253-017-4, с. 533 – 540
8. https://pulseenergy.io/blog/electric-vehicle-charging-station-with-solar-pv-panel-benefits

ПРАВНИ, ЕТИЧНИ И РЕГУЛАТОРНИ АСПЕКТИ НА СЪДЕБНОТО РЕШЕНИЕ

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LEGAL, ETHICAL AND REGULATORY ASPECTS OF THE JUDICIAL DECISION

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Abstract: *In judicial practice, digital mechanisms are used that facilitate the work of the court. Legal information products, such as APIS, CIELA, Lacorda, etc., are widely used, the information of which is an invaluable assistant in the study of judicial practice, its application and citation in almost every judicial decision. The penetration of artificial intelligence into various spheres and activities will inevitably lead to its use in issuing judicial acts. Nevertheless, it is necessary to preserve the role of the judge as a judicial authority so that digitalization and artificial intelligence do not lead to unlawful judicial acts, especially decisions, while preserving the principles of internal conviction, ethics and legal regulation of public relations in their judicial examination.*

Keywords: *artificial intelligence, digitalization, legal information products, case law, judge, judicial acts, ethics, legal regulation*

Повод за написването на това изследване стана едно скандално съдебно решение[1], което бе разпространено от колеги адвокати в публичното пространство с видимо възмущение и страховити коментари. След като и аз останах в недоумение от съдържанието му и проверих по всички достъпни начини съществуването на този съдебен акт[2], за да се убедя, че това не е (ако не друго) поне една

1 Вж. 1) https://www.facebook.com/photo?fbid=10237534693885117&set=pcb.10237534696405180 и 2) https://www.facebook.com/photo?fbid=10999913821629 36&set=a.623236579838421.

2Вж. 1) https://pleven-rs.justice.bg/bg/9815?from&to&actkindcode=5001&casenumber=6944&caseyear=2024&casetype=%D0%93%D1%80%D0%B0%D0%B6%D0%B4%D0%B0%D0%BD%D1%81%D0%BA%D0%BE&fbclid=IwY2xjawKa6v1leHRuA2FlbQIxMABicmlkETBWckYwVGhLemZ5dGpiQ2ViAR7SKh7Ba3TisV4S-

нелепа шега, не можех да остана безучастна. След което, в качеството си на натрупал немалко опит дългогодишен практикуващ адвокат и университетски преподавател, си позволих да напиша сигнал до Инспектората на Висшия съдебен съвет (ИВСС), до министъра на правосъдието и до административния ръководител – председателя на Плевенския районен съд. При това не за да придобия звездна популярност, а защото бях убедена, че е абсолютно недопустимо, в частност, в съдебната система и, като цяло, в правния свят да съществуват подобни „явления“. Признавам, че бях категорична в позицията си, но предпазлива относно авторството на акта, доколкото нямаше как да съм сигурна все пак доколко той е достоверен. Уви, впоследствие се оказа, че той не е бил плод на нечие въображение, а действително е постановен титул по висящо към онзи момент гражданско дело по описа на Плевенския районен съд: съдебно решение с рег. № 582/29.04.2025 г., което е оформено като годен съдебен акт, с автор съдия Светла Замфирова, в което е посочено, че то е постановено по гр.д. № 6944/2024 г. по описа на Плевенския районен съд, 13 граждански състав.

Накратко, съдържанието на посочения съдебен акт сочеше (меко казано) доста странни мотиви, които, както посочих и в сигнала си, буди съмнение дали авторството произхожда от човек, при това юрист, който се предполага, че е положил всички изискуеми по закон изпити, включително: семестриални и държавни, за юридическа правоспособност и магистратски. Или при написването му е използван изкуствен интелект. Или решението е нарочно създадено и разпространено в интернет като

WtHbJNszXA4FZ1FdN2Egem6VrAu-kuqx7d6sj0iu5qRqFg_aem_2Ci63VXBtazMk5Q-OJ_aug.

2) https://pleven-rs.justice.bg/bg/9815?from&to&actkindcode=5001&casenumber=6944&caseyear=2024&casetype=%D0%93%D1%80%D0%B0%D0%B6%D0%B4%D0%B0%D0%BD%D1%81%D0%BA%D0%BE&fbclid=IwY2xjawKa66hleHRuA2FlbQIxMABic mlkETBWckYwVGhLemZ5dGpiQ2ViAR7SKh7Ba3TisV4S-WtHbJNszXA4FZ1FdN2Egem6VrAu-kuqx7d6sj0iu5qRqFg_aem_2Ci63VXBtazMk5Q-OJ_aug.

3) chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://legalacts.justice.bg/Search/GetActContentByActId?actId=3LZGFPfleh ZD2rOE9HLtgg%3D%3D.

нелепа и доста груба шега. Или с цел да компрометира, или още по-лошо – опозори името на посочения съдия, съд, или въобще българската съдебна система.

Доколкото все пак не разполагах с каквито и да било правомощия, за да проверя достоверността на цитирания съдебен акт, намерих за уместно да предизвикам проверка на достоверността на акта и за предприемане на спешни мерки: или за опровергаването му и в защита на доброто име на магистрата Светла Замфирова, или, в случай на установена достоверност на решението, за предприемане на действия по санкционирането на лицето, постановило и подписало този акт, който дискредитира компетентността на съдията и компрометира и дори опозорява съдийската професия.

Всеки документ, който носи подпис (независимо саморъчен или електронен), установява авторството му. В конкретния случай подписът на съдията, освен че сочи авторството му, но така също води и до отговорност за написаното. И, въпреки че съдебната власт е независима, не е допустимо да се неглижира посредствеността и безотговорността, особено, когато става въпрос за решаване на човешки съдби и за произтичащите от това последици (при това без да е относим въпросът за крайния резултат, т.е. в чия полза е постановен акта).

Подчертавайки също така, че нито лично, нито служебно имам каквото и да било отношение по посоченото дело, че не познавам страните по спора, нито съдията, постановил (или набеден, че е постановил) акта, че нямам никакъв личен или служебен мотив, че не търся евтина популярност или сензация, изложих ясната си позиция за правната същност на акта.

Бях убедена, че в настоящия случай е необходимо сезирането на компетентните органи, с цел категоричното изключване на възможността за бъдещи унизителни приравнявания на достойните български юристи, включително магистрати, адвокати и др. с излезли извън рамките на високия професионализъм и висок морал изолирани случаи на самозабравили се „юристи“, заемащи отговорни позиции в обществото.

Така сигналът е стигнал три пъти до ИВСС: от мен, препратен от министъра на правосъдието и от председателя на Плевенския районен съд.

Получих три отговора, от всеки от сезираните със сигнала ми: първият – от министъра, който препраща сигнала на

Инспектората, вторият – от председателя на съда, който също препраща сигнала до Инспектората с позоваването на независимостта на магистрата при постановяването на своите актове и с уточнението, че против решението е подадена въззивна жалба, и третият – от Инспектората.

Становището, което получих от ИВСС, се свежда до формалното заключение: „По съществото си сигналите са насочени против правилността на съдебното решение. Като такива същите са неотносими към дейността на Инспектората към ВСС поради липса на правомощия. Последните са изрично определени в разпоредбата на чл. 54, ал.1, т.1 и т. 2 от Закона за съдебната власт и не предвиждат възможност за ревизия на правилността на съдебните актове. Такова правомощие има единствено горестоящият съд, по реда на инстанционния контрол.“.

В допълнение (година по-късно[3]) в Lex.bg News бе публикувана новина със заглавие „Съдийка няма да бъде наказана за разбирането си, че брачната изневяра е „углавно престъпление“.[4] От материала става ясно, че „Двата сигнала (очевидно моят и другият – на процесуалния представител на едната страна по делото, бел. моя) са разгледани от етичната комисия към Плевенския окръжен съд, която е изляза със становище, че Замфирова е уронила престижа на съдийската професия с написаното в мотивите към решението.“.

Без да съм запозната с мотивите на Етичната комисия към Плевенския окръжен съд, може да се направи извод, че становището на Комисията е правилно и законосъобразно, тъй като в Кодекса за етично поведение на българските съдии[5] са уредени „Основните принципи“ при упражняване на съдийската професия (Раздел I от Кодекса). А те са: независимост, безпристрастност, справедливост, почтеност, благоприличие, вежливост и толерантност, компетентност и квалифицираност и конфиденциалност.

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[3] *На 19 юни 2026 г.*

[4] *https://news.lex.bg/%D1%81%D1%8A%D0%B4%D0%B8%D0%B9%D0%BA%D0%B0-%D0%BD%D1%8F%D0%BC%D0%B0-%D0%B4%D0%B0-%D0%B1%D1%8A%D0%B4%D0%B5-%D0%BD%D0%B0%D0%BA%D0%B0%D0%B7%D0%B0%D0%BD%D0%B0-%D0%B7%D0%B0-%D1%80%D0%B0%D0%B7%D0%B1%D0%B8/.*

[5] *https://vss.justice.bg/root/f/upload/44/KEPBS12-12-24.pdf.*

В принципа за почтеност е включено правилото: „С поведението си в частния и в обществения живот съдията дава пример за висок морал и почтеност“ (изр. 3).

Благоприличието е определено като „въздържане от всякакви действия, които биха могли да компрометират честта на съдията в професията и обществото“.

„Компетентен и квалифициран е добре подготвеният съдия, който познава нормативната уредба на Република България, правото на Европейския съюз и международното право, който е развил способности и умения за тяхното коректно прилагане и непрекъснато се усъвършенства. Компетентността и квалифицираността са предпоставка за надлежното изпълнение на задълженията на магистрата и за неговото професионално израстване.“.

В Раздел II „Правила за етично поведение, произтичащи от основите принципи“ е предвидено: „Поведението на съдията трябва да съответства на високите морални качества, които са критерий за заемане на съдийска длъжност.“ (изр. 1 в т. 4.1. от „4. Правила за поведение, произтичащи от принципа за почтеност“), както и че „Съдията следва да се информира за съответните новости във вътрешното, европейското и международното право.“ (т. 7.4. от „7. Правила за поведение, произтичащи от принципа на компетентност и квалифицираност“).

В Раздел IV „Гаранции за спазването на въведените с този кодекс етични правила за поведение“ е посочен и компетентните органи по прилагането на правилата, предвидени в Кодекса: „Съдийската колегия на Висшия съдебен съвет осъществява цялостен контрол по прилагането и спазването на Етичния кодекс и периодично предприема действия за обновяване и актуализиране на предвидените с него правила. Комисията по професионална етика към Съдийската колегия на Висшия съдебен съвет и комисиите за професионална етика към органите на съдебната власт осъществяват пряк и непосредствен контрол по прилагането и спазването на Кодекса. Професионалните сдружения на съдиите предприемат предвидените в уставите им действия при всеки констатиран случай на допуснато нарушение на настоящите етични правила за поведение.“.

Продължението на сагата около съдебното решение и съдията, постановил акта, се свежда до това, че председателят на Плевенския районен съд е предложил на Съдийската колегия на ВСС

да образува дисциплинарно производство срещу съдия Замфирова. Колегията отказва по две причини: поради изтекла 6-месечната давност за образуване на дисциплинарно производство срещу съдийката и защото „кадровиците приемат предложението за недопустимо, защото фактическите основания, които се сочат като нарушение на етичния кодекс, попадат в обхвата на съдийската независимост и не могат да бъдат квалифицирани като нарушение на служебните нарушения или нарушаване на кодекса“.

И последната стъпка: тричленен състав на Върховния административен съд (ВАС) е отхвърлил жалбата на председателя на Плевенския районен съд срещу решението на Колегията, който, освен че приема мотивите на отказа, допълва: „В рамките на функционалния имунитет (чл. 132 от Конституцията на Република България) е дейността на съдията по осъществяване на правораздавателната му функция (чл. 117, ал. 2 от Конституцията на Република България), която може да бъде преценявана само по пътя на горестоящ съдебен контрол (инстанционен или извънреден). Неправилното тълкуване и приложение на материалния, респ. на процесуалния закон, не може да бъде основание за ангажиране на дисциплинарна отговорност на съдия“, посочва ВАС.“.

Независимо, че това решение на ВАС подлежи на обжалване до петчленен състав на същия съд, посочените факти са достатъчно притеснителни за бъдещето на правораздаването и за престижа на съдийската професия, чиято репутация е и без друго подложена на множество атаки в обществото.

Дотук с чисто практическата страна на казуса.

Проблемът е много по-дълбок, отколкото първоначално би могъл да се интерпретира. Да приемем, че това е изолиран случай от съдебната практика (и дай боже единствен!?). Той обаче поставя редица въпроси, свързани с бъдещото правораздаване, с оглед драстичното внедряване на информационните технологии, както и на изкуствения интелект. Какви ще бъдат съдебните актове, които ще се постановяват напред във времето? Не е ли прекалено рисковано да се ползва изкуственият интелект при решаването на правни спорове. И тук не става въпрос за косвеното му използване, като например, за законодателни справки или за

справки по съдебната практика[6], за граматични и правописни проверки на текстовете на актовете. Става въпрос за съдържателната част на актовете, които съдът трябва да постановява по вътрешното си убеждение, въз основа на съвкупната преценка на твърденията на страните и на събраните в конкретния съдебен процес доказателства, според нормите на закона. Механичното използване на изкуствения интелект не може да доведе до независими, безпристрастни, справедливи, почтени, благоприлични, вежливи, толерантни, компетентни, квалифицирани и конфиденциални действия на решаващия съдебен състав. То няма да доведе и до законосъобразни, правилни и справедливи съдебни актове. Типичен пример за това виждане изхожда от правилото, че съдът е длъжен по своето вътрешно убеждение да постанови своя акт, каквото изкуственият интелект няма и не може да има.

Безспорно, информационните и комуникационни технологии улесняват значително работата на съдиите, служителите в съда, адвокатите и въобще всички лица, които са ангажирани с практическото прилагане на правото[7]. Особено в периода на COVID пандемията от 2020 г. и в периода след нея, с въвеждането на електронното правосъдие[8], комуникацията се подобри и от гледна точка на бързина на процесуалните действия, и от гледна точка на достъпност, независимо от някои негативни проявления[9]. Но това е съвсем друга страна на правораздаването, положителна, която няма как да не се отчете.

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[6] *Тук засега също е много рисковано, доколкото, по мнението на специалистите, изкуственият интелект все още не е достигнал такова равнище, че да може да му се доверим напълно. Още повече, че в сферата на правото са създадени и функционират вече дълги години правно-информационни продукти, които са доказали своята ефективност: АПИС, СИЕЛА, ЛАКОРДА и др.*

[7] *Вж. Аракелян, Ванухи. Информационни и комуникационни технологии в съдилищата. Хронология, развитие, перспективи. // В: Предизвикателствата пред правото в контекста на дигитализацията: сборник с доклади от научна конференция, проведена в рамките на Лятната научна сесия на Юридическия факултет на Варненския свободен университет „Черноризец Храбър“. Секция „Право“, 29 юни – 1 юли 2018 г. ВСУ „Черноризец Храбър“. ISSN 1313-7263 (кн. 34, серия „Юридически науки и обществена сигурност“). 2018, с. 9 – 15.*

[8] *Вж. Колева, Милена. Единна информационна система на съдилищата. Въвеждане на електронно правосъдие в Република България. Сигурност на електронния обмен на данни. // В: Съвременни измерения на европейското образователно и научно пространство. ISSN 2367-7988. 2020, т. 8, с. 74 – 79.*

[9] *Вж. Босев, Росен. Проклятието „електронно правосъдие“: защо експериментът единна информационна система на съдилищата. Капитал. ISSN 1310-7984. 2020, год. 28, бр. 37, с. 24 – 25.*

Наред с положителните промени от въвеждането и използването на информационните технологии, включително и на изкуствения интелект, се засилва недоверието в качеството и даже в достоверността на всичко, което е създадено по изкуствен път и не представлява пряка човешка дейност въз основа на човешкото съзнание[10], включително мисъл, усещане, контрол.

Очевидно е, че правото, както и светът като цяло, вървят по дигитален път напред и няма да има връщане назад[11]. Но този път трябва да е застлан не с добри намерения, които да водят до ада, а с правни, етични и регулаторни механизми, които да гарантират законосъобразност, сигурност и доверие[12].

Навлизането на изкуствения интелект в различни сфери и дейности ще доведе неминуемо и до използването му при постановяване на съдебните актове. Независимо от това, необходимо е да се запази ролята на съдията като правораздавателен орган така, че при запазване на принципите за вътрешно убеждение, етичност и правно регулиране на обществените отношения при тяхното съдебно разглеждане, дигитализацията и изкуственият интелект да не доведат до незаконосъобразни съдебни актове, включително съдебни решения, определения и др. И това е необходимо преди всичко заради отговорността, която трябва да носи всеки правораздавателен орган, включително и преди всичко съдията.

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[10] Наумова, Стефка. Функционални особености на правното съзнание в условията на модерните информационни технологии. // В: Предизвикателствата пред правото в контекста на дигитализацията: сборник с доклади от научна конференция, проведена в рамките на Лятната научна сесия на Юридическия факултет на Варненския свободен университет „Черноризец Храбър“. Секция „Право“, 29 юни – 1 юли 2018 г. ВСУ „Черноризец Храбър“. ISSN 1313-7263 (кн. 34, серия „Юридически науки и обществена сигурност“). 2018, с. 16 – 24.

[11] Вж. Шеншин Виктор Михайлович, Попков Дмитрий Валерьевич. „Искусственный интеллект в сфере юриспруденции в эпоху цифровизации (начало)“ // Аграрное и земельное право, №. 5 (233), 2024, сс. 73-77. doi:10.47643/1815-1329_2024_5_73.

[12] Вж. Доверие в цифровом мире : монография / Ю. В. Веселов, С. Р. Карапетян, М. В. Белова [и др.] ; под редакцией Ю. В. Веселова. — Москва : Ай Пи Ар Медиа, 2023. — 206 с. — ISBN 978-5-4497-2073-3. — Текст : электронный // Цифровой образовательный ресурс IPR SMART : [сайт]. — URL: https://www.iprbookshop.ru/books/129057/details (дата обращения: 27.07.2026). — Режим доступа: для авторизир. пользователей.

Литература:

1. Аракелян, Ванухи. Информационни и комуникационни технологии в съдилищата. Хронология, развитие, перспективи. // В: Предизвикателствата пред правото в контекста на дигитализацията: сборник с доклади от научна конференция, проведена в рамките на Лятната научна сесия на Юридическия факултет на Варненския свободен университет „Черноризец Храбър“. Секция „Право“, 29 юни – 1 юли 2018 г. ВСУ „Черноризец Храбър“. ISSN 1313-7263 (кн. 34, серия „Юридически науки и обществена сигурност“). 2018, с. 9 – 15.
2. Босев, Росен. Проклятието „електронно правосъдие“: защо експериментът единна информационна система на съдилищата. Капитал. ISSN 1310-7984. 2020, год. 28, бр. 37, с. 24 – 25.
3. Жекова, Жанета. Проблеми на авторското право в ЕС във връзка с дигитализацията (Предложението за Директива относно авторското право в цифровия единен пазар). // В: Предизвикателствата пред правото в контекста на дигитализацията: сборник с доклади от научна конференция, проведена в рамките на Лятната научна сесия на Юридическия факултет на Варненския свободен университет „Черноризец Храбър“. Секция „Право“, 29 юни – 1 юли 2018 г. ВСУ „Черноризец Храбър“. ISSN 1313-7263 (кн. 34, серия „Юридически науки и обществена сигурност“). 2018, с. 67 – 71.
4. Колева, Милена. Единна информационна система на съдилищата. Въвеждане на електронно правосъдие в Република България. Сигурност на електронния обмен на данни. // В: Съвременни измерения на европейското образователно и научно пространство. ISSN 2367-7988. 2020, т. 8, с. 74 – 79
5. Наумова, Стефка. Функционални особености на правното съзнание в условията на модерните информационни технологии. // В: Предизвикателствата пред правото в контекста на дигитализацията: сборник с доклади от научна конференция, проведена в рамките на Лятната научна сесия на Юридическия факултет на Варненския свободен университет „Черноризец Храбър“. Секция „Право“, 29 юни – 1 юли 2018 г. ВСУ „Черноризец Храбър“. ISSN 1313-7263 (кн. 34, серия „Юридически науки и обществена сигурност“). 2018, с. 16 – 24.
6. Радев, Орлин. Дигиталната правна цивилизация/Digitalawzation. // В: Предизвикателствата пред правото в контекста на дигитализацията: сборник с доклади от научна конференция, проведена в рамките на Лятната научна сесия на Юридическия факултет на Варненския свободен университет „Черноризец Храбър“. Секция „Право“, 29 юни – 1 юли 2018 г. ВСУ „Черноризец Храбър“. ISSN 1313-7263 (кн. 34, серия „Юридически науки и обществена сигурност“). 2018, с. 38 – 45.

7. Доверие в цифровом мире : монография / Ю. В. Веселов, С. Р. Карапетян, М. В. Белова [и др.] ; под редакцией Ю. В. Веселова. — Москва : Ай Пи Ар Медиа, 2023. — 206 с. — ISBN 978-5-4497-2073-3. — Текст : электронный // Цифровой образовательный ресурс IPR SMART : [сайт]. — URL: https://www.iprbookshop.ru/books/129057/details (дата обращения: 27.07.2026). — Режим доступа: для авторизир. пользователей.
8. Шеншин Виктор Михайлович, Попков Дмитрий Валерьевич. „Искусственный интеллект в сфере юриспруденции в эпоху цифровизации (начало)“ // Аграрное и земельное право, № 5 (233), 2024, сс. 73-77. doi:10.47643/1815-1329_2024_5_73.

DIGITAL READING AND DIGITAL TWINS AS A FACTOR FOR LITERACY DEVELOPMENT IN EDUCATION 5.0

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Abstract: *In the context of Education 5.0, the development of literacy necessitates the integration of innovations that combine digital reading, personalized learning, and intelligent pedagogical analysis. The paper examines digital reading as a tool for developing reading, functional, and media literacy through interactivity and multimodality. Particular emphasis is placed on the role of Digital Twins as dynamic cognitive models designed to track academic progress and construct an adaptive learning environment. The theoretical framework is supported by an author-conducted empirical study among 317 respondents (primary school teachers and pedagogy students). The analysis reveals a discrepancy between the widespread utilization of digital resources and the limited awareness of the Digital Twins concept. Concurrently, the data indicate a high readiness among pedagogical specialists to implement software for tracking reading progress. This synergy opens new perspectives for effective literacy support tailored to the individual needs of each learner.*

Keywords: *digital pedagogy, digital reading, empirical research, Education 5.0, personalized learning, reading comprehension, Digital Twins*

Introduction

The dynamic changes in the information environment in recent years have questioned traditional notions of literacy. In modern scientific research, it is increasingly viewed as a complex competence that goes beyond traditional reading and writing skills, including the ability to think critically, work with digital resources, media literacy and effective communication in a digital environment (Dimitrova, 2024).

In the Bulgarian educational context, these processes find concrete expression in the introduction of digital platforms that support the organization of the learning process, communication between participants in education and the development of digital skills. In this regard, Mishkova-Yotova (2024) emphasizes that the Shkolo educational platform

opens up opportunities for the digitalization of the school environment and for more effective management of educational activities.

This new interpretation of the concept of "literacy" is most clearly reflected in the educational profile of today's students, particularly children of the "Alpha" generation, for whom digitalization has been a natural part of daily life since birth (Dimitrova, 2022). Although they have constant access to information and view the digital environment as a natural space for communication, international studies continue to report difficulties in comprehending, interpreting, and critically evaluating information in a digital environment. Thus, in the context of information overload, the focus in education is shifting from providing access to knowledge to developing cognitive strategies for selecting and effectively using that knowledge.

Today's students interact primarily with multimodal texts that combine verbal content, images, sound, and hyperlinks. This turns digital reading into a complex cognitive activity that shapes new patterns of reading behavior and requires the targeted development of digital media literacy among both students and teachers. (Dimitrova, 2024; Dimitrova, 2025).

Alongside the transformation of reading, the concept of Education 5.0 is also evolving, emphasizing personalized learning, smart educational environments, and the use of technology to support human development. In contrast to the technology-oriented models of digitization characteristic of previous stages of educational development, the 5.0 model views technology as a means of building a more humane, adaptive, and inclusive educational environment tailored to the individual needs of learners (Fisk, 2019; Haleem et al., 2022).

In view of the new educational philosophy, technologies based on data analysis and modeling of individual development of learners are attracting increasing interest. Among them, the concept of digital twins deserves special attention, which initially arose in engineering sciences, but gradually finds application in education. If in industry the digital twin represents a virtual copy of a physical object, in pedagogy it is considered as a dynamic model of the learner, which integrates data on his academic development, behavioral characteristics, preferred learning strategies and interaction with digital content in order to predict and optimize educational results (Furini et al., 2022).

The connection between digital reading and digital twins opens up new perspectives for personalized learning. Data generated from a student's interaction with digital text can help track individual progress and plan pedagogical activities tailored to their educational needs.

This report aims to analyze the possibilities of digital reading and digital twins as factors for the development of literacy in the context of Education 5.0. The emphasis is placed on the potential of these technologies for personalizing learning and creating intelligent educational environments that support the development of the modern student. The theoretical statements in the report are complemented by the results of an author's survey conducted among primary school teachers and students - future educators, aimed at establishing attitudes towards the use of digital technologies for the development of reading literacy and the possibilities for personalizing learning.

Theoretical framework of the study

The development of digital technologies has a significant impact on the way in which students perceive, process and use information. An increasing number of texts that children work with in school and outside it are presented in digital format and combine different channels of communication - text, image, sound, video and interactive elements. This specificity changes the nature of reading and places new demands on the development of reading literacy (Dimitrova, 2024).

In the scientific literature, digital reading is seen as a process that goes beyond traditional decoding and comprehension of text. It involves skills for navigating a hypertext environment, critically evaluating information sources, managing attention, and making sense of content presented in different formats (OECD, 2023). Unlike linear reading on paper, digital reading requires continuous choice between different information paths, which puts the student in an active position as a researcher and constructor of knowledge.

Research shows that digital educational resources can increase motivation to read and support comprehension through the use of multimedia elements and interactive tasks. At the same time, they create prerequisites for superficial perception of information and difficulties in in-depth analysis of text content (Carr, 2010). Therefore, modern pedagogy is faced with the need to combine the advantages of digital technologies with strategies for the development of critical thinking and reading comprehension.

In this regard, the potential of generative artificial intelligence can also be highlighted as a means of stimulating language development, creative thinking and active participation of students in the primary educational stage. Mishkova-Yotova and Kolarova (2025) examine the application of ChatGPT in combination with the “fantasy binomial” method in creating fairy tales in the second grade and emphasize the possibilities of this

approach for developing imagination, narrative skills and motivation for learning.

This problem is especially relevant in the primary educational stage, when basic reading habits and strategies are formed. According to Dimitrova (2025), the use of digital tools in education can be an effective mechanism for developing reading literacy, when combined with targeted methodological support and pedagogical management of the reading process.

Personalized learning as a feature of Education 5.0

Contemporary educational policies are placing an increasingly clear emphasis on the need for instruction tailored to students' individual characteristics. This trend is reflected in the concept of Education 5.0, which views technology as a means of supporting human development and creating more flexible and inclusive educational environments.

One of the key characteristics of Education 5.0 is the personalization of learning. This involves adapting the curriculum, the pace of learning, and the methods used to the needs, interests, and abilities of each individual student. At the center of the educational process is not technology itself, but the learner and their development (Fisk, 2019). Implementing such a model involves the use of tools for collecting and analyzing educational data, which provide information about students' progress, the challenges they face, and their preferred learning strategies. In this way, teachers are able to plan instruction more effectively and provide individualized support where it is needed.

In the context of reading literacy development, a personalized approach allows for more accurate identification of reading difficulties and creates conditions for timely pedagogical intervention. This is particularly important in elementary school, when differences in the pace of development among individual students are often significant.

Digital twins and opportunities for literacy development

Among the new technological solutions that have attracted researchers' attention in recent years are digital twins. In the broadest sense, a digital twin is a virtual model that is updated with real-time data and enables the tracking, analysis, and prediction of specific processes. In an educational context, this means creating a dynamic model of the learner that integrates information about their knowledge, skills, achievements, and learning behavior (Furini et al., 2022).

Of particular interest is the possibility of using digital twins to track processes related to reading. Data on reading speed, time spent on a text, errors made, strategies used, and the level of comprehension can provide valuable information about a student's individual development. Analyzing such data would allow for more precise instructional planning and the creation of personalized learning paths.

Of course, the implementation of such technologies also raises a number of questions related to data privacy, the ethical aspects of monitoring, and the need for high digital competence among educators. Regardless of these challenges, digital twins point to a promising direction for the development of smart educational environments in which technology supports, rather than replaces, pedagogical interaction.

In this sense, the interaction between digital reading, personalized learning and digital twins can be seen as one of the possible directions for the development of literacy in the context of Education 5.0. It is this interrelationship that lays the foundation for the empirical research presented in the next part of the report.

Research methodology

This empirical study aims to examine the attitudes of current and future elementary school teachers toward the use of digital reading and digital technologies in education, as well as the potential of digital avatars to support personalized learning and the development of reading literacy. The main research question concerns determining the readiness of the two target groups to apply such technologies in educational practice.

The study includes 317 respondents. The first group consists of 172 elementary school teachers from various regions of the country, while the second group consists of 145 education students from Burgas Free University. This sample structure allows for a comparison between the attitudes of practicing teachers and those of future educators.

A questionnaire was used to collect the empirical data. The questionnaire included closed-ended and scale-based questions aimed at determining the extent to which digital technologies are used in teaching, familiarity with the concept of digital twins, attitudes toward personalized learning, as well as the perceived benefits and risks of implementing such technological solutions. The data obtained were processed using quantitative analysis and are presented as percentage values.

The results make it possible to track the main trends in the attitudes of current and future teachers toward the use of digital technologies for

developing reading literacy and personalizing instruction in the context of Education 5.0.

Results and discussion

The analysis of the empirical data outlines positive attitudes among current and future teachers toward the use of digital technologies in the educational process. The results show that digital tools already play a significant role in teaching, but at the same time reveal limited awareness of some of the latest technological solutions related to personalized learning.

The indicator "use of digital tools in teaching" reveals a high degree of technology application in pedagogical practice. A total of 85% of respondents indicated that they use digital resources in the teaching process or in their own professional development. This result confirms the trend toward the increasingly widespread integration of digital tools into the educational environment and is consistent with findings from other studies related to the development of digital pedagogy.

Of particular interest are the results regarding familiarity with the concept of "digital twins." The data show that only 18% of respondents are familiar with the term "digital twin." There is a significant discrepancy between the active use of digital technologies and awareness of newer concepts related to intelligent educational systems. This is likely due to the fact that the concept has not yet become widely established in educational theory and practice and is more often discussed in the context of engineering and information sciences.

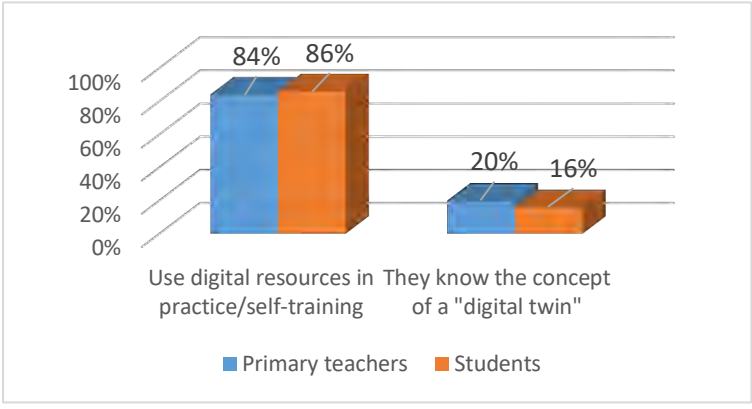


Fig. 1. Use of digital technologies and knowledge of the concept of digital twins among surveyed teachers and students.

The data in *Figure 1* illustrate the contrast between the high level of use of digital resources and the limited understanding of the concept of digital twins. This highlights the need for a more targeted presentation of

contemporary technological trends in both the training of future teachers and in continuing education programs.

The results regarding personalized learning are particularly telling. A total of 92% of respondents believe that an individualized approach is necessary for the effective development of students and for improving the quality of educational outcomes. This result demonstrates a high degree of agreement with one of the core ideas of Education 5.0 - placing the learner at the center of the educational process and adapting the learning environment to their individual needs.

Directly related to this is the observed willingness to use systems that analyze students' progress in reading. A total of 74% of participants stated that they would use such technological solutions in their practice. Although most respondents are unfamiliar with the concept of a "digital twin," the results indicate a positive attitude toward technologies based on the tracking and analysis of educational data for the purpose of more effective planning of pedagogical support.

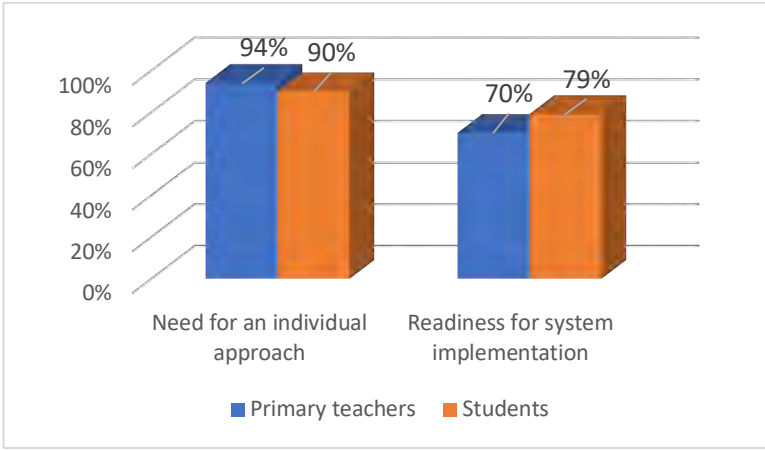


Fig. 2. Attitudes towards personalized learning and the use of technology to track reading progress.

As the data in *Figure 2* show, participants demonstrate a high degree of acceptance of the personalized approach and a willingness to use technologies that support the adaptation of instruction to students' individual progress.

Based on the results obtained, the following conclusions can be drawn:

(1) Digital technologies are now an integral part of educational practice and are perceived as an effective tool for developing reading literacy;

(2) there is a discrepancy between the active use of digital resources and familiarity with emerging concepts such as digital twins;

(3) current and future teachers demonstrate a high level of readiness to apply personalized approaches and technologies for tracking learning progress.

These findings highlight the need to expand the training of educators in the field of smart educational technologies and confirm their potential to support literacy in the context of Education 5.0.

Conclusion

The conducted research shows that current and future teachers demonstrate a positive attitude towards the use of digital technologies in the educational process and clearly realize the importance of a personalized approach to the development of reading literacy. Despite the limited awareness of the concept of digital twins, the participants show a willingness to use systems that analyze learning progress and support pedagogical decision-making. These results can be seen as an indicator of the presence of a favorable environment for the future implementation of intelligent educational technologies.

Digital twins are still a relatively new concept in educational practice, but their potential for tracking individual development, early identification of difficulties and personalization of learning makes them a promising direction for the development of modern educational systems. Combined with the capabilities of digital reading, they can contribute to the construction of adaptive educational environments that support the development of literacy in accordance with the needs of each learner.

In conclusion, it can be summarized that digital reading and digital twins have significant potential to become an important factor in the development of literacy in the context of Education 5.0. However, the realization of this potential requires targeted training of pedagogical specialists, development of digital competencies and creation of conditions for responsible and ethical use of educational technologies. Only with such an approach can technological innovations become a means for higher quality, inclusive and future-oriented education.

References:

1. Dimitrova, Z. (2022). Pedagogical aspects of the phenomenon of "digital childhood" and the digital socialization of children from the "Alpha" generation. Modern Humanities, 18 (1). BFU, 6–27.

2. Dimitrova, Z. (2024). "Alpha" Children and Digital Reading: Shaping a New Type of Reader. *The phenomenon of "language literacy" - primary school age*, 86–97, "St. Cyril and Methodius" University Publishing House.
3. Dimitrova, Z. (2025). Digital tools to support reading comprehension in primary education – attitudes and challenges for teachers. *BFU Yearbook*, 252–272.
4. Carr, N. (2010). *The Shallows: What the Internet is Doing to Our Brains*. W. W. Norton & Company.
5. Dimitrova, Z. (2024). Digital non-reality: Pedagogical approaches to involving "Alpha" children in the digital world. *Pedagogy*, 96(1S), 7–20. https://doi.org/10.53656/ped2024-1s.01
6. Fisk, P. (2019). Education 4.0 … the Future of Learning Will Be Dramatically Different, In School and Throughout Life.
7. Furini, M., O. Gaggi, S. Mirri, M. Montangero, E. Pelle, F. Poggi, C. Prandi. (2022). Digital twins and artificial intelligence. // Communications of the ACM, 65 (2), pp. 98-104.
8. Haleem, A., Javaid, M., Qadri, M. A., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. *Sustainable Operations and Computers, 3*, 275–285.
9. Mishkova-Yotova, I. (2024). Presentation of the opportunities for digitization in the Bulgarian school through the educational platform "Shkolo": Trends and perspectives. Knowledge - International Journal, 62(2), 233–236.
10. Mishkova-Yotova, I., & Ivanova Kolarova, T. (2025). Artificial Intelligence and the Fantasy Binomial: Creative Fairy Tale Writing (Based on Gianni Rodari) in Second Grade. Knowledge - International Journal, 67(5), 771–777.
11. OECD. (2023). *PISA 2022 Results*. OECD Publishing.

STRATEGIC INNOVATION MANAGEMENT THROUGH NETWORK INTERACTIONS in SMEs

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Abstract: *The report examines the strategic management of innovation in small and medium-sized enterprises through the prism of network interactions. The aim is not only to systematize and analyze the leading theoretical positions in the field, but also to propose an original hybrid model of an innovation network, applicable in the context of SMEs. It unites key components of the innovation process, including input resources, processes of informal interactions and idea generation, subsequent formalization in partnerships and projects, as well as the implementation of innovations. The model has a dynamic and cyclical nature and demonstrates how the interaction between formal and informal networks leads to the creation of innovations, competitive advantage and organizational growth.*

Keywords: *strategic innovation management, network interactions, SMEs, open innovation, hybrid model, competitive advantage*

Introduction

In this context, strategic innovation management through network interactions is emerging as a key mechanism to overcome these limitations. Contemporary literature highlights that innovations are increasingly less often the result of internal efforts of individual organizations, and are more often generated within cross-sectoral and inter-organizational networks. The concept of "open innovation" implies the active use of external sources of knowledge and cooperation with various partners such as suppliers, customers, universities and other companies [2]. In this sense, network interactions not only expand access to resources, but also support the processes of creating and implementing innovations. Empirical research shows that participation in innovation networks has a positive impact on the innovation and business performance of SMEs, and this effect is often mediated by the ability of firms to transform external knowledge into innovation outcomes [3]. This draws attention to the role of absorptive capacity as a key organizational capability that allows for the identification, absorption

and application of external knowledge [4]. In addition, the structural characteristics of networks – such as density, diversity of partners and strength of ties – have a significant impact on innovation outcomes [5]. The presence of strong and heterogeneous ties facilitates access to diverse knowledge and resources, which in turn stimulates innovation activity [3]. At the same time, informal interactions based on trust and prior relationships often play a critical role in the early stages of idea generation and collaboration [6]. From a strategic management perspective, the effective use of network interactions requires integration with the firm's internal resources and capabilities. Theoretical frameworks such as the resource-based approach and the Dynamic Capabilities theory emphasize the importance of firms' ability to combine internal and external resources to achieve sustainable competitive advantage [7]. In this context, networks can be seen as a strategic resource that contributes to building competitive advantages through access to knowledge, technology, and markets. Despite significant research progress, there is a need for integrative models that bring together the different aspects of network interactions and their role in the innovation process. This paper aims to propose a hybrid model of an innovation network that brings together input resources (knowledge, contacts, capital), informal and formal interaction processes, and outputs in the form of innovation, competitive advantage, and growth. Through a synthesis of existing theoretical and empirical research, the report seeks to contribute to a better understanding of the mechanisms through which SMEs can strategically manage their network interactions in order to enhance their innovation performance.

1. Theoretical framework of network interactions in the formation of innovations in SMEs

The modern understanding of the innovation process in SMEs is characterized by a clear shift away from linear models of innovation towards systemic and network interpretations that emphasize the interaction between multiple actors. This transformation is conditioned both by the increasing complexity of the technological environment and by the structural constraints of SMEs related to limited access to resources, knowledge and research capacity. In this context, network interactions are asserted not simply as a complementary mechanism, but as a fundamental prerequisite for innovation activity. A number of theoretical concepts consistently emphasize the positive relationship between participation in networks and innovation outcomes, with access to external knowledge and resources being seen as a key factor in overcoming internal constraints [8] [3]. However, a

significant part of the literature remains at the level of establishing correlations, without offering a sufficiently in-depth explanation of the mechanisms through which network interactions are transformed into specific innovation outcomes. This leads to a certain conceptual fragmentation, where networks are seen as a "black box", without a clear distinction between the processes within it.

The concept of open innovation offers an important theoretical perspective, emphasizing that organizations need to purposefully integrate external and internal sources of knowledge into the innovation process. In the context of SMEs, this approach is particularly relevant, as it compensates for the limitations of internal resources by engaging in wider networks of partners. Despite its explanatory power, the theory of open innovation is often criticized for remaining at a relatively high level of abstraction and not sufficiently taking into account the internal dynamics of interactions, especially the role of informal ties and the social context, which are critically important for SMEs [9]. In this sense, the integration of the concept of absorptive capacity complements the analysis by providing a microfoundation for understanding how firms extract value from external knowledge. The ability to recognize, assimilate, and apply new information has been identified as a key mediator between network participation and innovation outcomes [10] [4]. However, existing research often views absorptive capacity as a static characteristic, ignoring its evolutionary and processual nature, especially in the context of dynamic network structures. Dynamic capabilities theory extends this analysis by emphasizing the need for organizations not only to absorb knowledge, but also to actively reconfigure their resources and interactions in response to a changing environment. However, the application of this theory to SMEs is limited by the assumption of sufficient organizational capacity for strategic resource management - an assumption that is often not valid in the context of small firms with limited managerial resources [11]. A further complication arises from the structural characteristics of networks. Research shows that the diversity of partners and the presence of weak ties create conditions for access to new knowledge, while strong ties and trust support its effective absorption and implementation [5] [6]. However, the literature often considers these features in isolation, without analysing their interaction over time and their role in the different stages of the innovation process. This is particularly problematic for SMEs, where the boundaries between formal and informal interactions are blurred and dynamic. A significant contribution to the understanding of network interactions in SMEs is made by studies that highlight the role of partners as active co-creators of

innovation, rather than simply as sources of resources [12]. However, these studies also reveal that the effect of networks is not unambiguously positive, but depends on the ability of enterprises to manage the complexity of interactions and to balance openness and control. Despite significant progress in the theoretical understanding of network interactions, there is a clear lack of a framework that unifies the different levels of analysis - from input resources and social interactions, through organizational capabilities, to the processes of formalization and implementation of innovations. Current approaches either focus on the structural characteristics of networks or on the internal capabilities of firms, without explaining clearly enough how these elements are linked into a single, dynamic process. This theoretical gap is particularly relevant in the context of SMEs, where innovations often emerge as a result of a combination of informal interactions, gradually formalized partnerships and adaptive organizational practices. It is this need for integration that justifies the development of a hybrid innovation network model that simultaneously reflects the structural, process and behavioral dynamics of innovation.

2. Analysis of existing models of innovation networks

The analysis of existing models of innovation networks shows considerable conceptual diversity, but also reveals a number of limitations, especially in terms of their applicability to small and medium-sized enterprises. Several dominant approaches can be identified in the literature, which consider network interactions as a key mechanism for generating and diffusing innovations, but often remain fragmented in terms of the process logic and internal dynamics of interactions. The model of innovation systems, including national and regional innovation systems, emphasizes the institutional environment and interactions between organizations such as enterprises, universities and public structures [13] [14]. This approach offers a valuable macro-framework for understanding innovation processes, but is criticized for its aggregation and limited ability to explain the micro-level of interactions, especially in the context of SMEs, where informal ties and individual initiatives play a significant role. In this context, the Triple Helix model complements the analysis by emphasizing the interaction between universities, industry and government as a driver of innovation [15]. Despite its analytical value, this model is often criticized for its normative nature and for assuming a relatively high level of institutional coordination, which is rarely available in SMEs. Furthermore, it does not sufficiently take into account the role of informal networks and entrepreneurial ecosystems, which are critical for small firms. An extension of the triple

helix model is the concept of the Quadruple Helix, which includes civil society, media and consumers as a fourth element [16]. This model emphasizes that innovations are not created solely within the framework of interactions between science, business and state institutions, but are also shaped under the influence of societal needs, cultural factors and processes of co-creation of value. In this way, the understanding of the innovation process is broadened by including end-users as active participants in it. It should be noted that the model remains relatively abstract in terms of the mechanisms through which societal input is transformed into concrete innovation outcomes, especially in the context of SMEs.

Another important theoretical approach is the concept of clusters, which considers the geographical concentration of interconnected firms and institutions as a factor for increasing innovation activity [17]. The cluster model emphasizes the importance of proximity, trust and shared resources, but its application is limited in the context of digitalization and globalization, where innovation networks increasingly transcend geographical boundaries. In addition, not all SMEs have access to well-developed clusters, which calls into question the universality of this model. Of particular importance for the analysis of innovation in SMEs is the concept of entrepreneurial ecosystems, which considers innovation activity as a result of interactions between entrepreneurs, investors, universities, government institutions and supporting organizations [18]. Unlike traditional models, this approach places the entrepreneur at the center of the system and emphasizes the importance of local conditions, culture and access to resources. Despite its practical applicability, the concept often suffers from the lack of a unified theoretical framework and from difficulties in measuring the interrelationships between the individual components of the ecosystem. The network approach to innovation, based on social network theory, offers a more micro-analytical perspective, examining the structure and quality of connections between actors. This approach emphasizes the importance of weak ties and structural holes for access to new information and ideas. However, it often remains focused on structural characteristics of networks, without sufficiently integrating the processes of transformation of ideas into concrete innovations, as well as the mechanisms of formalization and implementation.

Modern models of innovation ecosystems seek to overcome some of these limitations by considering innovations as the result of dynamic, multi-stakeholder interactions in open systems [19] [20]. These models emphasize the role of coordination, co-creation of value, and interdependencies between actors. However, they often remain too broad and

insufficiently specific regarding the internal processes in SMEs, as well as the transition from informal interactions to formalized innovation outcomes.

3. Conceptual hybrid model of an innovation network in SMEs

The identified limitations in existing theoretical models of innovation networks necessitate the development of a more integrated analytical framework that simultaneously takes into account the resource constraints of SMEs, the importance of informal interactions and the process nature of innovation. In this context, this study proposes a hybrid model of an innovation network that synthesizes elements of the theory of open innovation, dynamic capabilities and the network approach to innovation. The proposed model conceptualizes the innovation process as a dynamic system structured in three interconnected components: input, process and output, with the emphasis on the transformational role of network interactions.

The input component includes access to knowledge, resources and contacts that arise both from the internal environment of the enterprise and from external networks and partners. In line with the concept of open innovation, SMEs do not rely solely on internal resources, but actively integrate external sources of knowledge, including customers, suppliers, scientific organizations and other firms. However, this input should not be seen as a static resource set, but as a result of the positioning of the enterprise in the network and the quality of its connections. The process component represents the main innovation dynamic and includes three consecutive but interrelated phases. The first covers informal interactions, within which ideas are generated through information exchange, experience sharing and social contacts. It is particularly critical for SMEs, as it compensates for the lack of formalized research and development structures. The second phase includes the formalization processes, in which initial ideas are transformed into concrete partnerships, projects or contractual relationships. Here the role of organizational capabilities for coordination and management of interactions is manifested. The third phase is related to the implementation of the innovation, which includes the transformation of the developed solutions into marketable products, services or processes. The output component of the model reflects the results of the innovation process, which can be viewed as competitive advantage, increased innovation capability or organizational growth. Unlike traditional models that consider outcomes primarily as economic indicators, the proposed model also emphasizes the accumulation of network capital and organizational knowledge as key long-term effects.

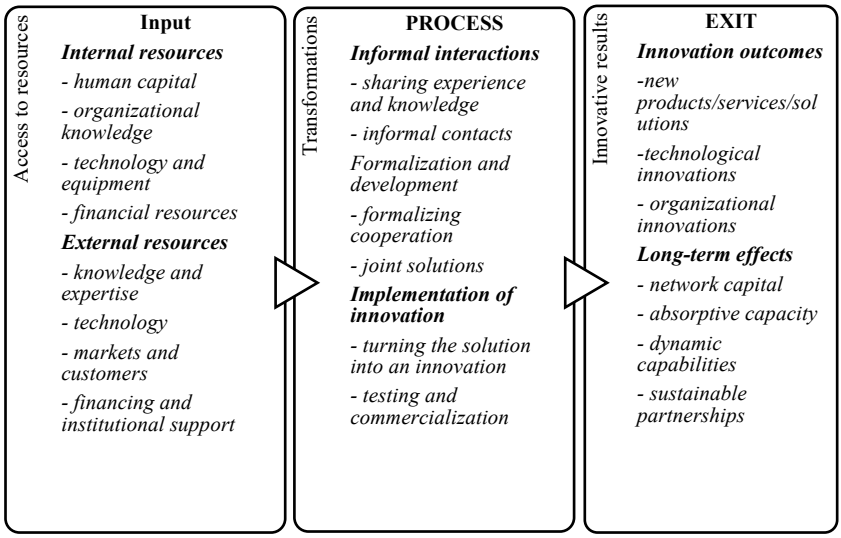


Fig. 1 Conceptual hybrid model of innovation network in SMEs
Source: Author's constructions

The contribution of the hybrid model is the integration of informal and formal interactions into a single process logic. While existing models often consider these two types of interactions in isolation, the current approach treats them as sequential and interdependent stages in the development of innovation. Furthermore, the model has the potential to overcome the limitations of static resource-oriented approaches by emphasizing the dynamic transformation of resources through network interactions. In contrast to theories that assume the presence of significant organizational capacity, the proposed model takes into account the role of limited resources and emphasizes flexibility, entrepreneurial orientation and the ability to use external connections as a substitute for internal resources.

4. Conclusion

This study examines the strategic management of innovation in SMEs through the lens of network interactions, emphasizing the need for an integrated and process-oriented approach. The analysis of leading theoretical concepts – including open innovation, dynamic capabilities and network theories – has shown that each of them contributes significantly to the understanding of innovation processes, but at the same time remains limited in its ability to explain the overall dynamics of interactions in the context of SMEs. A critical review of existing models has revealed the lack of an integrated framework that connects input resources, informal and formal

interactions and final innovation outcomes. There is a deficit of models that reflect the role of informal networks, social capital and the adaptability of small firms in conditions of limited resources and high uncertainty. The practical application of scientific research, a systematic approach to sharing innovations and know-how transfer, strategic management of intellectual assets and accelerated cooperation between stakeholders are essential for improving the innovation capacity of organizations, but they still do not find a high degree of integration in European innovation policies [1]. In this context, a hybrid innovation network model has been proposed, which conceptualizes the innovation process as a dynamic system of interconnected elements. The main contribution of the model lies in the integration of informal and formal interactions into a single process logic. The model takes into account the specificities of SMEs, including limited resources, flexibility and dependence on external sources of knowledge, thus offering a higher degree of applicability in a real business environment. In this way, the traditional understanding of the results of innovation activity is expanded, including not only economic effects, but also the accumulation of network capital, organizational knowledge and long-term adaptation capabilities. This allows for a more complete assessment of the impact of network interactions on the sustainable development of enterprises. The development contributes both theoretically and practically, offering a conceptual basis for more effective innovation management in SMEs. Future research could be aimed at empirically testing the model, as well as at investigating the influence of specific network characteristics on the innovation performance of enterprises.

References:

1. European Commission: Directorate-General for Research and Innovation, „Science, research and innovation performance of the EU, 2024 : a competitive Europe for a sustainable future : executive summary.," Office of the European Union, 2024.
2. S. Brunswicker u W. Vanhaverbeke, „Open innovation in small and medium-sized enterprises (SMEs): External knowledge sourcing strategies and internal organizational facilitators," Journal of Small Business Management, 53(4), p. 1241–1263, 2015.
3. S. Gronum, M. Verreynne u T. Kastelle, „The role of networks in small and medium-sized enterprise innovation and firm performance," Journal of Small Business Management, 50(2), p. 257–282., 2012.

4. L. Benhayoun, M. Le Dain u C. Dominguez-Péry, „The role of absorptive capacity in SMEs' innovation: A systematic literature review," Journal of Small Business Management, 59(S1), pp. 1-36, 2021.
5. A. J. J. Pullen, P. C. de Weerd-Nederhof, A. J. Groen u M. Song, „Successful patterns of internal SME characteristics leading to high overall innovation performance," Creativity and Innovation Management, 21(2), p. 209–223, 2012.
6. A. Lipparini, u M. Sobrero, „The glue and the pieces: Entrepreneurship and innovation in small-firm networks," Journal of Business Venturing, 9(2), p. 125–140, 1994.
7. D. J. Teece, „Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance," Strategic Management Journal, 28(13), p. 1319–1350, 2007.
8. R. Rothwell, u M. Dodgson, „External linkages and innovation in small and medium-sized enterprises," R&D Management, 21(2), p. 125–137, 1991.
9. H. W. Chesbrough,, „Open innovation: The new imperative for creating and profiting from technology," Harvard Business School Press, 2003.
10. W. M. Cohen u . D. A. Levinthal,, „Absorptive capacity: A new perspective on learning and innovation.," Administrative Science Quarterly, 35(1), p. 128–152, 1990.
11. D. J. Teece,, G. Pisano, u A. Shuen,, „Dynamic capabilities and strategic management," Strategic Management Journal, 18(7), p. 509–533, 1997.
12. S. Durst, A. Mention u P. Poutanen, „Service innovation and its impact: What do we know about?," Investigaciones Europeas de Dirección y Economía de la Empresa, 26(2), p. 65–72, 2020.
13. B. Lundvall, National systems of innovation: Towards a theory of innovation and interactive learning., Pinter Publishers, 1992.
14. R. R. Nelson, , National innovation systems: A comparative analysis, Oxford University Press, 1993.
15. H. Etzkowitz u L. Leydesdorff, „The dynamics of innovation: From national systems and "Mode 2" to a triple helix of university–industry–government relations," Research Policy, 29(2), p. 109–123, 2000.
16. E. Carayannis u D. Campbell, „Mode 3 and Quadruple Helix: Toward a 21st Century Fractal Innovation Ecosystem," HomeInternational Journal of Technology Management, том 46, pp. 201-234, 2009.
17. M. E. Porter, „Clusters and the new economics of competition,"Harvard Business Review, 76(6), p. 77–90, 1998.
18. E. Stam, „Entrepreneurial Ecosystems and Regional Policy: A Sympathetic Critique," European Planning Studies, том 23, № 9, p. 1759–1769, 2015.
19. R. Adner, „Match your innovation strategy to your innovation ecosystem," Harvard Business Review, 84(4), p. 98–107, 2006.

E. Autio u L. D. W. Thomas, , „Innovation ecosystems: Implications for innovation management," ß The Oxford handbook of innovation management, Oxford, Oxford University Press, 2014, p. 204–228.

PEDAGOGICAL MODELS FOR DIGITAL READING IN THE CONTEXT OF TRANSFORMATION TOWARDS A CIRCULAR FUTURE

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Abstract: *Contemporary education is undergoing an intensive digital transformation that places new demands on the development of literacy and digital competencies from the earliest stages of schooling. This paper examines pedagogical models for digital reading as a tool for modernizing the learning process through interactivity, multimodality, adaptability, and personalized learning. It analyzes contemporary approaches, including interactive e-books, adaptive educational platforms, gamification, artificial intelligence applications, and digital twins, which support the development of reading and functional literacy. Particular emphasis is placed on the potential of these models to foster key competencies and to implement a cyclical model of learning oriented toward sustainable development and preparing students for the challenges of a circular future.*

Keywords: *digital reading, primary school, reading literacy, pedagogical models, digital twins, educational circularity, circular future*

Introduction

Modern education is undergoing a profound structural transformation driven by the digitization of society, the dynamic renewal of information, and new demands for global sustainability. These processes call for a rethinking of traditional educational models and shift the focus toward a competency-based approach. In this approach, the students' abilities to discover, interpret, and apply knowledge in a variety of life and professional situations take on a leading role (OECD, 2019; Chavdarova-Kostova, 2022).

In this context, concepts related to the sustainable development of education and the preparation of students for a future characterized by a high degree of technological dynamism, social interconnectedness, and the need for continuous learning are becoming increasingly important. Among

these, the vision of a “circular future” deserves special attention, as it emphasizes the sustainable development of knowledge, skills, and competencies as a prerequisite for adaptability and lifelong learning.

Basic literacies and key competencies play a leading role in this fundamental shift in the field of education, as they are viewed as the foundation for an individual’s successful participation in the knowledge society. Reading literacy and digital competence are of particular importance in this regard, as they create the conditions for effective interaction with the ever-growing flows of information and digital resources (European Union, 2018).

Early education plays a key role in this process, because it is during this stage that the foundations of reading comprehension, learning skills, and the first manifestations of digital literacy are laid. In today’s educational environment, these are increasingly realized through the use of digital technologies, which are changing the way students perceive, process, and interpret information (UNESCO, 2021).

In the Bulgarian educational context, digital transformation is specifically manifested in the use of educational platforms that support the organization of the learning process, communication among educational stakeholders, and the development of digital skills. In this regard, Mishkova-Yotova (2024) highlights the capabilities of the Shkolo platform for digitizing the school environment and for more effective management of educational activities.

Among the most significant manifestations of this change is digital reading, which expands traditional practices for working with text by integrating multimodal content, interactive resources, and opportunities for personalized learning. This necessitates the development and implementation of new pedagogical models that can combine the development of reading literacy with the cultivation of competencies necessary for successful participation in the digital society.

This report examines pedagogical models for digital reading as a systematic tool for achieving educational transformation aligned with the principles of a circular future. The analysis focuses on their potential for developing functional literacy and digital competence, taking into account the age-specific characteristics of students and the particularities of instruction at the elementary education level. The study is based on the understanding that digital reading should not be viewed solely as a technological tool for accessing information, but as a pedagogical mechanism that supports the sustainable development of cognitive

experience and creates conditions for achieving contemporary educational goals.

Theoretical foundations of the study

The idea of a circular future in education applies the principles of the circular economy to an educational context, viewing knowledge not as an end product but as a renewable educational resource. In this sense, learning is interpreted not as a one-time act of acquisition, but as a process of continuous construction, application, and transformation of knowledge. This conceptual framework is finding increasingly broad support in international research on sustainable development, where the transfer of circular management from economic systems to educational culture is viewed as a leading strategy for the future (Rotondo et al., 2025). The process of integrating circular principles into educational programs requires the development of comprehensive conceptual models that realign the learning environment with the needs of sustainable development (Serrano-Bedia, Perez, 2022; Rotondo et al., 2025).

Unlike traditional linear models of learning, which often emphasize the short-term reproduction of knowledge, the circular educational logic involves a continuous cycle of acquisition, application, reflection, and reintegration of what has been learned. In this way, the educational process functions as a self-renewing system in which each new cognitive activity activates the student's prior experience and transforms it into a higher level of competence. This dynamic shifts the focus from immediate educational outcomes to the sustainability of learning—the ability of students to transfer and adapt acquired knowledge to new and unfamiliar situations (OECD, 2019). It is precisely this sustainability that is regarded as one of the key characteristics of future-oriented education.

Basic Literacy Skills and Key Competencies in the Context of Circular Education

Basic literacies (reading, mathematical, digital, functional, and scientific) constitute the essential cognitive foundation of educational development. They should not be viewed merely as a set of technical skills, but rather as dynamic abilities to interpret, analyze, and apply information in a variety of contexts.

In a circular education context, literacies take on additional significance. They not only provide access to knowledge but also play an active role in its reinterpretation, expansion, and reapplication. In our previous studies, we have argued that reading literacy in the early stages

of education goes far beyond the process of decoding written text and manifests itself as a mechanism for repeatedly constructing and reconstructing meaning in various learning situations (Dimitrova, 2022; Dimitrova, 2024).

At the same time, the key competencies outlined in European educational policies integrate the knowledge, skills, and attitudes necessary for personal fulfillment, social inclusion, and active participation in public life (European Union, 2018). In this study, they are viewed not as a stage following literacy skills, but as the result of constant interaction between them. Competencies such as critical thinking, communication, collaboration, creativity, initiative, learning skills, digital literacy, and civic engagement are formed as early as the literacy development process and develop in parallel with it.

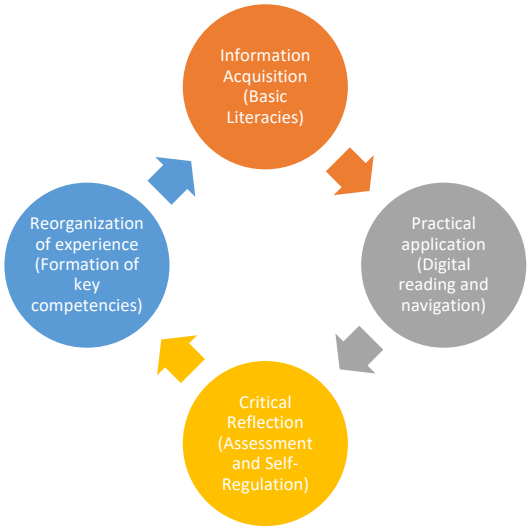
Digital Reading as a Link Between Literacy and Competencies

In the age of digitalization, reading is gradually becoming a complex multimodal process that goes beyond the traditional interaction between reader and text. Digital reading involves working with a variety of information formats—text, images, sound, video, and hypertext links—that function as an interconnected system for constructing meaning (Dimitrova, 2024). Thus, when working in a digital environment, students do not simply absorb information but actively select, evaluate, interpret, and integrate it. This requires the development of new cognitive and metacognitive strategies related to navigating digital content, critically evaluating information sources, managing attention, and making informed choices among different information alternatives.

From this perspective, digital reading serves as a bridge between basic literacy skills and key competencies. It creates conditions for the simultaneous development of reading literacy, digital competence, critical thinking, and self-regulated learning skills, which are necessary for effective participation in the knowledge society.

Conceptual model of educational circularity

The theoretical frameworks presented can be summarized using a conceptual model of educational circularity, as shown in Scheme 1.



Scheme 1. Conceptual model of educational circularity

As shown in *Scheme 1*, the proposed model interprets learning as a cyclical and self-renewing process carried out through four interrelated stages: information acquisition, practical application, critical reflection, and reorganization of experience.

- **Information assimilation** - at this stage, the student draws on their basic literacy skills to comprehend and interpret information presented in various modalities—text, images, sound, or video. In digital reading, the decoding process takes place in a multimodal environment that requires the simultaneous processing of diverse informational stimuli.
- **Practical Application** - the information learned is transformed into action through solving educational problems, working on real-world scenarios, participating in interactive activities, or using digital educational resources. In this way, knowledge moves from the level of perception to the level of application, which creates the conditions for its meaningful understanding and long-term retention.
- **Critical Reflection** - during this stage, the student analyzes the information received, evaluates its reliability, and relates the new knowledge to existing cognitive structures. Skills such as critically evaluating sources, managing attention, and consciously interacting with digital content take on particular importance.

- **Reorganization of experience** - the final stage of the cycle is characterized by the integration of newly acquired knowledge and skills into the student's existing cognitive experience. As a result of this reorganization, previous cognitive structures are enriched and transformed, leading to the development of a higher level of competence and laying the groundwork for a new cycle of learning.

In this way, the model presents learning not as a linear accumulation of knowledge, but as a process of continuous transformation and building upon cognitive experience. It is precisely this cyclical nature that we define as **educational circularity**, in which each new learning situation activates prior knowledge, places it in a new context, and creates conditions for its subsequent development. Consequently, **digital reading serves as a mechanism that facilitates the implementation of the circular model of learning by combining basic literacy skills, metacognitive processes, and key competencies**.

Pedagogical models for digital reading - from technological innovation to educational sustainability

The development of digital technologies over the past two decades has led to significant changes in reading practices and in the ways students interact with information. Alongside traditional printed texts, digital resources that combine various modes of presentation—text, images, sound, animation, and interactive elements—are becoming increasingly widespread. This technological evolution naturally raises the question of the need for new pedagogical models that can support the development of reading literacy in a digital environment.

In the academic literature, digital reading is most often examined through the lens of technological innovations and opportunities to improve learning effectiveness. The focus is usually on the multimodality of content, the interactivity of digital resources, the personalization of learning, and the use of algorithms to adapt the learning process to learners' individual characteristics (Leu et al., 2017; Coiro, 2012). Despite the significant number of studies in this field, the perspective that views digital reading as a mechanism for realizing sustainable and cyclical learning processes is relatively underrepresented.

In the context of the concept of a circular future, pedagogical models for digital reading can be interpreted not only as technological solutions but also as tools for building educational sustainability. Their value

extends beyond simply providing access to information; it lies in their ability to create conditions for the repeated use, reinterpretation, and transformation of knowledge in various educational and real-life situations. In this way, digital reading becomes a means of realizing educational circularity, in which learning takes place through successive cycles of acquisition, application, reflection, and building upon experience.

From this perspective, this study examines pedagogical models for digital reading as a bridge between basic literacy skills and key competencies. They provide opportunities for the development of reading literacy, digital competence, critical thinking, and self-regulated learning skills, which are among the main prerequisites for active participation in the knowledge society and for successful adaptation to the challenges of the future.

In the academic literature and contemporary educational practice, several main pedagogical models for digital reading can be identified, which are applied in elementary education.

1. Model of interactive digital reading

Interactive digital reading is one of the earliest and most widespread models for integrating technology into the reading process. Its main feature is the active interaction between the student and the digital text through various interactive elements—hyperlinks, animations, audio commentary, embedded questions, and self-assessment tasks. In this way, the reader does not merely passively absorb information but becomes an active participant in the process of constructing meaning (Dimitrova, 2024).

Interactive e-books are widely used in early education. According to Takacs, Swart, and Bus (2015), multimedia elements such as animations, sound effects, and visual cues can aid text comprehension and vocabulary development among younger students. These resources increase motivation to read, with the positive effect being most pronounced when technological features are aligned with educational goals and support the cognitive processing of information rather than distracting from it.

In circular education, interactive reading creates the conditions for repeatedly revisiting the same content through different educational pathways. Students can go through the text multiple times, activating previously acquired knowledge with each subsequent interaction and linking it to new pieces of information. In this way, the reading process becomes a cycle of continuous rethinking and building upon cognitive experience.

In elementary education, this model supports the development of reading literacy, skills for extracting and interpreting information, and the

ability to navigate independently in a digital environment. It is precisely these characteristics that make it one of the first steps toward building more complex competencies related to critical thinking and self-regulated learning.

2. Model of multimodal reading

One of the most significant characteristics of the modern digital environment is the multimodality of information. Unlike traditional printed text, in which meaning is constructed primarily through linguistic means, digital resources combine various sign systems—written text, images, sound, video, animation, and interactive elements. This changes both the reading process and the cognitive mechanisms through which information is understood (Dimitrova, 2024).

The theoretical foundations of multimodal reading are linked to the research of Kress (2010), according to whom meaning is created through the interaction between different modalities, rather than solely through written language. In the context of digital communication, readers must simultaneously interpret verbal, visual, and auditory messages, integrating them into a unified structure of meaning. For this reason, reading is increasingly viewed as a complex activity involving the processing of multimodal information.

In elementary school, multimodal reading offers significant pedagogical opportunities. The age-specific characteristics of students in grades 1 through 4 call for the active use of visual aids and illustrations, which support the understanding of textual content. Combining text with images, animations, or audio explanations facilitates the establishment of connections between different pieces of information and supports the formation of more durable cognitive representations.

At the same time, multimodality also places new demands on reading. Students must develop skills for selecting relevant information, establishing connections between different information sources, and critically evaluating their reliability. In this way, the model contributes not only to the development of reading literacy but also to the development of digital literacy and critical thinking skills.

Through the lens of a circular future, multimodal reading expands the possibilities for reusing and reinterpreting knowledge. The same information can be presented through different modalities and subsequently interpreted in a variety of learning contexts. This creates conditions for the continuous reconstruction of cognitive experience and

supports processes of educational circularity, in which knowledge develops through successive cycles of application and transformation.

3. Adaptive digital reading model

One of the leading trends in the development of modern educational technologies is the shift from standardized to personalized learning models. At the heart of adaptive digital reading lies the idea that different students have different rates of development, different interests, and different support needs. Therefore, effective learning requires the flexible adaptation of content and learning tasks to the individual characteristics of learners.

Adaptive systems use algorithms to analyze learning performance and, based on the collected data, suggest appropriate texts, exercises, and levels of difficulty. A study by Holmes et al. (2019) shows that such technologies create opportunities for more precise tracking of progress and for the timely provision of pedagogical support.

In reading instruction, the adaptive model allows students to work with texts that correspond to their current level of reading proficiency. This reduces the risk of both excessive difficulty and a loss of motivation due to tasks that are not challenging enough. Personalization helps foster a positive attitude toward reading and creates conditions for greater engagement in the learning process.

This model is particularly important in elementary school, where differences in the pace of literacy development among individual students are often significant. Through adaptive technologies, the teacher is able to organize differentiated support without disrupting the overall logic of the learning process.

From the perspective of a circular future, adaptive reading embodies the principle of sustainable development of competencies. Each subsequent learning activity builds on previously acquired experience and creates conditions for its gradual expansion. In this way, the educational process becomes a coherent system of interconnected cycles of development, tailored to each student's individual educational trajectory.

4. A gamified model of digital reading

In recent years, gamification has established itself as one of the most promising approaches for increasing student motivation and active participation in the educational process. It is based on the integration of game mechanics into non-game contexts with the aim of stimulating engagement, persistence, and intrinsic motivation for learning. Deterding

et al. (2011) argue that gamification involves the use of elements such as missions, levels, points, badges, challenges, and feedback systems that encourage active student participation.

A similar logic applies to the use of interactive educational platforms that combine game elements, immediate feedback, and a competitive element. Mishkova-Yotova (2025) examines the Kahoot app as an online platform for interactive content that supports the acquisition and reinforcement of new vocabulary through students' active participation in a game-based learning environment.

In digital reading, the gamified model transforms interaction with the text into a series of cognitive challenges. Instead of merely completing tasks that involve reproducing information, students engage in activities that require them to identify meaningful connections, solve problems, uncover hidden information, and defend their own positions. In this way, reading becomes an active exploratory experience.

This model is particularly significant in early education, as play remains a natural mechanism for learning at this stage. Through digital platforms and educational apps, situations can be created in which reading comprehension is integrated into game scenarios featuring virtual characters, missions, and educational adventures. This contributes both to the development of reading literacy and to fostering a positive attitude toward learning.

From the perspective of a circular future, gamification creates conditions for repeatedly practicing and refining the same competencies in different contexts. Each subsequent level or challenge requires drawing on prior knowledge and applying it to a new situation. In this way, learning takes on a cyclical nature, and the development of competencies is achieved through successive processes of application, reflection, and building upon prior knowledge.

In addition to cognitive outcomes, the gamified model also influences the development of social-emotional skills such as resilience in the face of failure, self-regulation, collaboration, and initiative. It is precisely these qualities that are considered an essential part of a student's competency profile in the knowledge society.

5. A model of digital reading using artificial intelligence and digital twins

The development of artificial intelligence marks the beginning of a new phase in the evolution of digital reading and educational technologies. Unlike traditional digital resources, intelligent systems not only provide

content but also analyze learners' behavior, identify their difficulties, and offer personalized support strategies. According to Luckin (2016), artificial intelligence has the potential to expand opportunities for individualized learning and to assist teachers in making pedagogical decisions.

In elementary education, artificial intelligence can be used not only to adapt instructional content but also to stimulate language development, creative thinking, and the creation of original texts. In a study on the application of ChatGPT and the "fantasy binomial" method in creating fairy tales in second grade, Mishkova-Yotova and Kolarova (2025) highlight the potential of generative artificial intelligence to stimulate students' imagination, storytelling skills, and creative engagement.

When teaching reading, intelligent systems can track reading speed, comprehension levels, the frequency of errors, and patterns of interaction with the text. Based on this data, personalized recommendations are generated for additional exercises, adapted texts, or appropriate learning strategies. This allows for more precise tailoring of instruction to the needs of each student.

Of particular interest is the concept of the digital twin, which is gradually gaining traction in educational research. A digital twin can be defined as a dynamic virtual model of the learner that integrates information about their knowledge, skills, achievements, difficulties, and preferences in the learning process. Unlike traditional assessment systems, which reflect a student's current status, the digital twin makes it possible to track development over time and predict future educational needs.

In grades 1.–4., such an approach could facilitate the early identification of difficulties in reading and text comprehension, as well as the planning of timely interventions. At the same time, the teacher's role remains central, as technological solutions cannot replace the pedagogical judgment, emotional support, and social interaction that are the foundation of effective learning.

Looking toward a circular future, artificial intelligence and digital twins can be viewed as tools for the sustainable management of educational development. Through the continuous collection and analysis of information on learning progress, conditions are created for the consistent development of competencies and the implementation of personalized learning cycles. Thus, knowledge is not viewed as a static outcome of learning, but as a dynamic system that continuously evolves and adapts to the changing needs of the learner.

Digital Reading and the Skills of the Circular Future

An analysis of the pedagogical models examined shows that digital reading is establishing itself as much more than a technological tool for accessing information. It functions as a comprehensive pedagogical environment in which reading literacy, digital competence, critical thinking, and self-regulated learning skills are developed simultaneously. The models examined place the student in an active role as a researcher, interpreter, and creator of meaning.

From the perspective of a circular future, the significance of these models lies in their ability to support the sustainable development of knowledge and competencies. Through repeated application, reflection, and transfer of what has been learned to new contexts, they create the conditions for the continuous expansion of cognitive experience. In this way, digital reading becomes a mechanism for fostering adaptability, critical thinking, and a readiness for lifelong learning - qualities that are considered essential for personal fulfillment in contemporary society.

Results and Conclusion

The theoretical analysis conducted allows us to draw several key conclusions regarding the role of digital reading in the context of the transition to a circular future.

1. Digital reading should be viewed not only as a technological tool for accessing information, but as an independent pedagogical mechanism for developing basic literacy skills and key competencies. Its significance stems from its ability to integrate cognitive, metacognitive, and digital processes into a unified educational environment.

2. Contemporary pedagogical models for digital reading expand upon traditional text-based practices through interactivity, multimodality, adaptability, and personalized learning. This creates the conditions for greater student engagement and more effective development of skills in understanding, analyzing, and critically evaluating information.

3. Digital reading supports the sustainable development of competencies. Through opportunities for repeated application, reflection, and the transfer of knowledge to various learning situations, conditions are created for the development of adaptability, independence, and a readiness for lifelong learning.

4. The concept of a circular future offers a productive theoretical framework for interpreting learning processes in a digital environment. In this regard, digital reading can be viewed as a means of realizing educational circularity, in which knowledge and competencies are

developed through continuous building upon, transforming, and applying them in new cognitive situations.

In conclusion, it can be argued that the effective integration of pedagogical models for digital reading in elementary education creates the conditions for preparing students who are capable of learning, adapting, and functioning successfully in a society oriented toward sustainable development, innovation, and the continuous renewal of knowledge.

References:

1. Dimitrova, Zl. (2022). Digital reading as a methodological approach in teaching Bulgarian language and literature at primary school age, Libraries, Reading, Communications: Twentieth National Scientific Conference with International Participation. Veliko Tarnovo. ISSN 2683-0981 (online)/ISSN 1313-8138 (Print).
2. Dimitrova, Zl. (2024). "Alpha" Children and Digital Reading: Shaping a New Type of Reader. *The phenomenon of "language literacy" - primary school age* (pp. 86–97). House "St. Cyril and Methodius" University Publishing.
3. Chavdarova-Kostova, S. (2022). A manual for implementing the competency-based approach in the training of future teachers. Ministry of Education and Science.
4. Coiro, J. (2012). The new literacies of online reading comprehension: Future directions. The Educational Forum, 76(4), 412–417. https://doi.org/10.1080/00131725.2012.708620
5. Council of the European Union. (2018). *Council Recommendation of 22 May 2018 on key competences for lifelong learning (2018/C 189/01).* Official Journal of the European Union, C189, 1–13.
6. Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: Defining “gamification”. In Proceedings of the 15th International Academic MindTrek Conference (pp. 9–15). ACM. https://doi.org/10.1145/2181037.2181040
7. Holmes, W., Bialik, M., & Fadel, C. (2019). Artificial intelligence in education: Promises and implications for teaching and learning. Center for Curriculum Redesign. https://curriculumredesign.org/our-work/artificial-intelligence-in-education/
8. Kress, G. (2010). Multimodality: A social semiotic approach to contemporary communication. Routledge.
9. Leu, D. J., Kinzer, C. K., Coiro, J., Castek, J., & Henry, L. A. (2017). New literacies: A dual-level theory of the changing nature of literacy, instruction, and assessment. Journal of Education, 197(2), 1–18. https://doi.org/10.1177/002205741719700202

10. Luckin, R. (2016). Intelligence unleashed: An argument for AI in education. Pearson. https://www.pearson.com/content/dam/one-dot-com/one-dot-com/global/Files/about-pearson/innovation/Intelligence-Unleashed-Publication.pdf
11. Mishkova-Yotova, I. (2024). Presentation of the opportunities for digitization in the Bulgarian school through the educational platform "Shkolo": Trends and perspectives. Knowledge - International Journal, 62(2), 233–236.
12. Mishkova-Yotova, I. (2025). Application of the online platform for interactive content „Kahoot!" for mastering and strengthening new vocabulary in English language. Knowledge - International Journal, 70(2), 255–261.
13. Mishkova-Yotova, I., & Ivanova Kolarova, T. (2025). Artificial Intelligence and the Fantasy Binomial: Creative Fairy Tale Writing (Based on Gianni Rodari) in Second Grade. Knowledge - International Journal, 67(5), 771–777.
14. OECD. (2019). OECD Learning Compass 2030: Concept Notes. OECD Publishing.
15. Rotondo, B., Bakker, C., Balkenende, R., & Arquilla, V. (2025). Integrating circular economy principles in the new product development process: A systematic literature review and classification of available circular design tools. Sustainability, 17(9), Article 4155. https://doi.org/10.3390/su17094155
16. Serrano-Bedia, A.-M., & Pérez-Pérez, M. (2022). Transition towards a circular economy: A review of the role of higher education as a key supporting stakeholder. Sustainable Production and Consumption, 31, 82–96. https://doi.org/10.1016/j.spc.2022.02.001
17. Takacs, Z. K., Swart, E. K., & Bus, A. G. (2015). Benefits and pitfalls of multimedia and interactive features in technology-enhanced storybooks: A meta-analysis. Review of Educational Research, 85(4), 698–739. https://doi.org/10.3102/0034654314566989
18. UNESCO. (2021). Reimagining our futures together: A new social contract for education. Report from the International Commission on the Futures of Education. UNESCO.

ENHANCING RENEWABLE ENERGY INTEGRATION UNDER A UNDER EVOLVING CROSS-BORDER ELECTRICITY FLOW DYNAMICS

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Abstract: *This paper examines the transformation of power systems from a model based on continuous electricity generation toward an On-Demand (OD) management paradigm driven by the increasing penetration of renewable energy sources (RES). Based on empirical data for Bulgaria covering the period 2015–2025, key changes in the daily electricity profile are identified, characterized by energy surpluses during periods of high solar generation and deficits during evening peak demand hours. The study investigates the role of cross-border electricity exchange, pumped-storage hydropower plants, and energy storage systems as key instruments for the implementation of an energy regulation mechanism and the provision of operational flexibility. A conceptual framework for On-Demand energy management is proposed, in which economic efficiency is achieved through optimization of temporal price spreads rather than through maximization of electricity generation volumes. The results indicate that this approach leads to a fundamental transformation in the role of national power systems—from providers of baseload electricity generation to suppliers of highly flexible energy services with increased added value.*

Keywords: *Renewable Energy Integration, On-Demand Energy Integration (ODEI), Power System Flexibility, Energy Storage Systems, Cross-Border Electricity Exchange, Adaptive Power System Architecture*

I. Introduction

European power systems are undergoing a profound transformation driven by decarbonization policies, the accelerated deployment of renewable energy sources, the digitalization of system management, and the increasing need to enhance the resilience of electricity markets. The growing share of variable renewable generation is reshaping conventional models of electricity production, transmission, and consumption, imposing new

requirements on power system balancing, security of supply, and cross-border coordination.

The Republic of Bulgaria occupies a strategic position within the electricity infrastructure of Southeast Europe due to its geographical location, well-developed transmission network, and the availability of substantial generation capacity, including nuclear power generation, conventional thermal power plants, and an increasing share of renewable energy sources. Under conditions of deepening European electricity market integration, the country's role is gradually evolving from that of a traditional electricity producer and exporter toward becoming an active participant in the regional management of electricity flows.

Contemporary developments within the European power system require the adoption of new analytical approaches based on the assessment of cross-border energy flows, electricity demand dynamics, the impact of renewable energy sources, and advances in energy storage technologies. At the same time, digitalization and the implementation of intelligent control systems create opportunities for improving the efficiency of the electricity sector through forecasting, optimization, and adaptive operational management [1–3].

Particular attention should be given to the analysis of changes in electricity imports and exports observed in recent years, which indicate a shift in regional interaction patterns among individual countries. The traditional understanding of electricity exchange as a mechanism for covering temporary supply deficits is gradually being replaced by a concept of strategic energy flow management based on economic optimization, system resilience, and integrated regional planning.

Within this context, the present study aims to analyze the evolution of electricity flows in Bulgaria during the period 2019–2025 and to assess the country's role within the changing European energy landscape. Particular emphasis is placed on the interrelationship between cross-border electricity exchange, the development of generation capacity, and the need to implement modern management and strategic planning frameworks.

The scientific contribution of this study lies in the development of an integrated analytical approach that combines the assessment of generation performance indicators, cross-border energy flows, and the factors determining regional power system resilience, thereby providing a foundation for the future development of digitally assisted power system management mechanisms.

II. Methodology

This study employs a comprehensive analytical approach to assess the impact of renewable energy sources (RES) on the operation of the Bulgarian power system under conditions of a changing structure of regional electricity flows. The methodological framework combines quantitative analysis of electricity sector indicators, comparative assessment of cross-border electricity exchange, and systems engineering principles for evaluating structural transformations within the electricity infrastructure [4–6].

The analysis covers the period 2019–2025, characterized by the accelerated deployment of renewable energy sources, increasing European market integration, and evolving regional patterns of electricity interaction. The selected timeframe enables the identification of trends before and after significant changes in the European energy landscape, including decarbonization processes, electricity market dynamics, and transformations in the nature of international energy flows.

For the purposes of the study, a methodology consisting of the following sequential stages was applied.

Stage 1. Power System Balance Analysis

An assessment of the structure of the electricity system was carried out through the analysis of:

- electricity generation;
- cross-border electricity imports;
- cross-border electricity exports;
- net electricity balance;
- changes in load profiles;
- contribution of renewable energy sources.

This assessment enables the evaluation of the evolving role of different generation technologies in maintaining the resilience and operational stability of the power system.

Stage 2. Analysis of Cross-Border Electricity Flows

Changes in electricity exchange between Bulgaria and neighboring countries were investigated through an analysis of:

- import and export flow dynamics;
- regional balancing dependencies.

Particular attention was devoted to changes in the significance of individual interconnection corridors and their influence on overall power system resilience.

With the increasing degree of interconnection and regional coordination, transmission system operators (TSOs) operate in an environment of

growing interdependence among electricity markets. This development is closely associated with the ongoing European energy transition and the digitalization of power system management processes.

Stage 3. Systems Engineering Analysis

To evaluate the impact of renewable energy sources on system operation, a systems engineering approach was applied, including:

- analysis of power system flexibility;
- assessment of balancing capacity requirements;
- evaluation of the role of electricity storage technologies;
- impact on cross-border electricity transmission and transit flows.

A conceptual framework was employed to assess the interactions between electricity generation, regional electricity exchange, and power flow management mechanisms [7–9].

Stage 4. Conceptual Model for Adaptive Energy Management

The proposed concept addresses the need to enhance the adaptability of power systems under conditions of increasing generation flexibility and growing penetration of renewable energy sources.

A conceptual On-Demand Energy Integration (ODEI) model is proposed, in which the power system operates through dynamic interactions among the functional layers of generation, forecasting, balancing, regional electricity exchange, and market optimization.

The operational logic of the model is based on the sequential processing of data related to renewable energy generation, electricity demand, available storage capacity, cross-border electricity exchange, and market signals. Following short-term forecasting, the system determines the current state of the electricity balance and selects the optimal operational response depending on the existence of an energy surplus or deficit (Figure 1).

In the event of an energy surplus, the model prioritizes energy storage, regional electricity exchange, and market-based energy allocation. In deficit conditions, balancing resources, stored energy reserves, and adaptive demand-side management mechanisms are activated to maintain system stability and operational reliability.

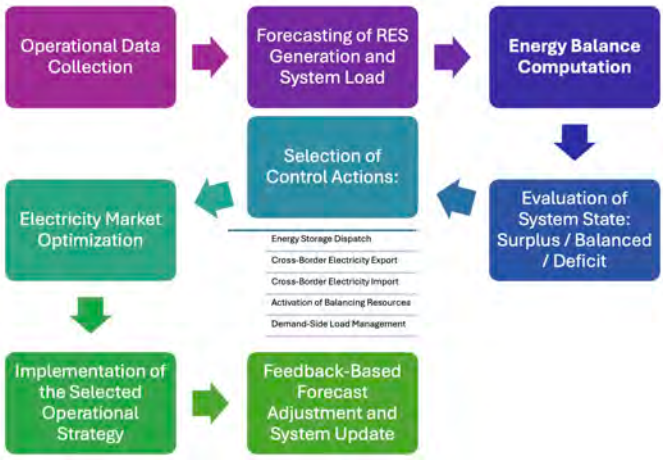


Figure 1 *Operational Workflow of the Proposed On-Demand Energy Integration (ODEI) Model*

III. Challenges of Renewable Energy Integration under a Changing Cross-Border Electricity Flow Model

The accelerated deployment of renewable energy sources within the European power system creates significant opportunities for reducing carbon emissions and increasing the share of clean energy generation. At the same time, however, it introduces substantial changes in the operation and management of electricity networks. The generation characteristics of photovoltaic and wind power plants are inherently variable, fundamentally altering the traditional principles governing power system operation and control [10–13]. The conventional power system paradigm is based on predictable generation from baseload power plants and the adjustment of generation output according to electricity demand. Under conditions of high renewable energy penetration, an inverse relationship emerges, where electricity consumption patterns and system flexibility must increasingly adapt to the availability of renewable generation. This transition results in the emergence of a new operational paradigm for power system management, in which system resilience depends on the coordinated operation of several key components:

- renewable generation forecasting;
- cross-border electricity exchange;
- balancing resources;
- electricity storage technologies;
- digital demand-side management;
- market-based optimization mechanisms.

3.1. Variability of Renewable Generation and Its Impact on the Power System Balance

One of the primary technical challenges associated with renewable energy integration is the dependence of generation on external environmental conditions. Photovoltaic power plants are highly sensitive to cloud cover, seasonal variations, and daily solar cycles, while wind power plants exhibit substantial fluctuations in output due to changing meteorological conditions.

Periods of high solar generation frequently result in temporary electricity surpluses during daylight hours, followed by a rapid decline in generation during the evening period. This phenomenon leads to significant fluctuations in balancing requirements and increases the operational burden on transmission system operators.

A comparison of Figure 2 and Figure 3 clearly demonstrates the significant impact of photovoltaic generation on the overall generation structure of the Bulgarian power system. During periods of high solar production, photovoltaic generation becomes the dominant source of electricity, substantially reducing the contribution of conventional and dispatchable generation resources. This effect highlights the growing importance of operational flexibility, energy storage technologies, and cross-border electricity exchange in maintaining power system balance under high renewable energy penetration conditions.

In power system engineering, this phenomenon is commonly associated with the so-called Duck Curve effect, characterized by:

- a reduction in conventional generation during midday hours;
- the formation of a pronounced evening demand peak;
- the need for rapid ramping of dispatchable generation resources;
- increased dependence on energy storage systems and regional electricity exchange.

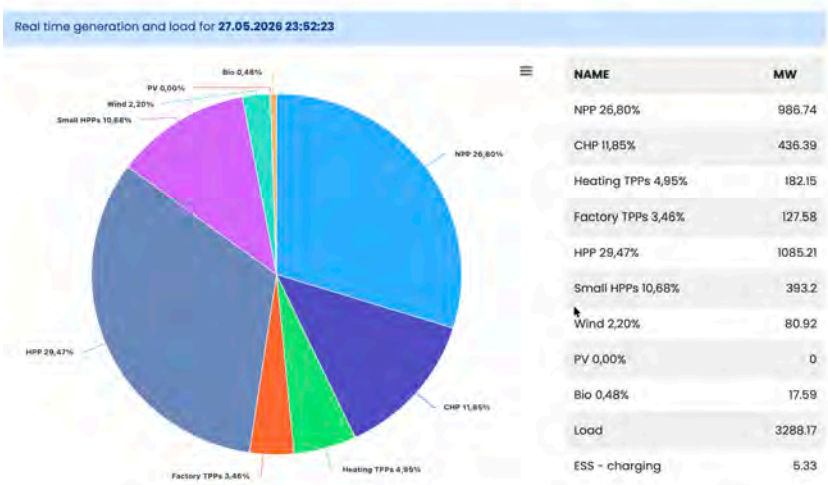


Figure 2 Generation structure of the Bulgarian power system during periods without photovoltaic generation (27 May 2026, 23:52)

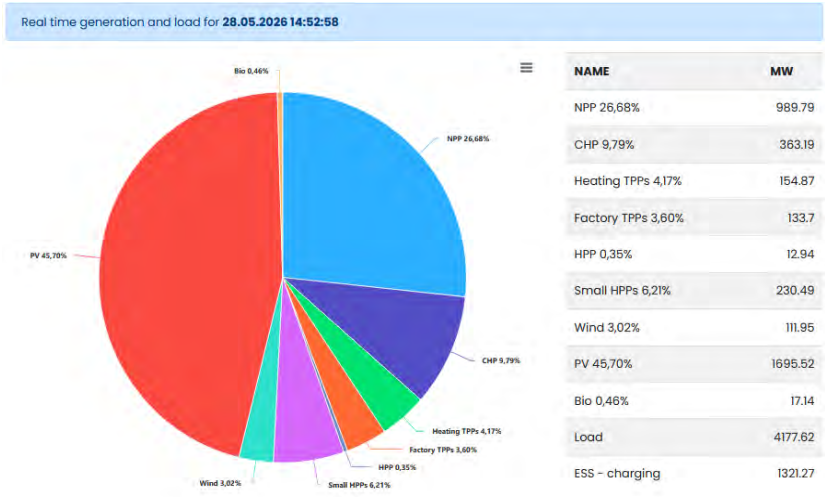


Figure 3 Generation structure of the Bulgarian power system during daytime operation with high photovoltaic penetration (28 May 2026, 14:52)

In power systems with a high share of renewable energy sources, the management of these dynamic fluctuations gradually becomes a determining factor for maintaining security of electricity supply.

3.2 Need for Enhanced Power System Flexibility

Power system flexibility refers to the capability of an electricity system to respond effectively to short-term and medium-term variations in

generation and demand without compromising the quality, reliability, and security of electricity supply.

The principal technical instruments for enhancing system flexibility include:

Balancing Resources

Conventional power plants continue to play a critical role in maintaining frequency stability and compensating for short-term generation deficits.

Pumped-Storage Hydropower Plants (PSHPPs)

Pumped-storage hydropower plants enable the conversion of surplus electricity into stored potential energy, which can subsequently be utilized during periods of increased electricity demand.

Battery Energy Storage Systems (BESS)

Lithium-ion and hybrid energy storage technologies provide opportunities for:

- peak load reduction;
- minimizing renewable energy curtailment;
- stabilizing the electricity balance;
- improving the efficiency of cross-border electricity exchange.
- Demand-Side Management

Intelligent demand management systems enable electricity consumption patterns to be adjusted in accordance with available generation resources, thereby contributing to improved operational flexibility and system efficiency.

3.3 Cross-Border Electricity Flows and Regional Integration

Modern power systems operate within an environment characterized by a high degree of interconnection and interdependence. Coordination among transmission system operators is becoming increasingly important due to growing cross-border electricity flows and the rising variability of generation patterns [14,15].

The development of European electricity infrastructure is gradually shifting the traditional concept of nationally managed power systems toward a regionally coordinated electricity network. The European Network of Transmission System Operators for Electricity (ENTSO-E) provides mechanisms for operational coordination, market integration, and enhanced reliability of electricity supply across interconnected regions [16,17].

Bulgaria occupies a strategically important position within this framework due to its well-developed transmission infrastructure and extensive interconnections with neighboring countries. The transmission network serves as a key infrastructure asset for the long-distance transfer of electricity through high-voltage and extra-high-voltage transmission lines, enabling efficient regional energy exchange.

As the penetration of renewable energy sources continues to increase, interconnection capacity is progressively evolving from a reserve mechanism for ensuring reliability into an active instrument for the operational balancing of regional power systems.

IV. Analysis of Cross-Border Electricity Flows in Bulgaria During the Period 2019–2025

Changes in the structure of electricity flows over recent years represent one of the most significant indicators of the ongoing transformation of the Bulgarian power system. The accelerated deployment of renewable energy sources, increasing regional market integration, and changes in the European energy landscape have contributed to the emergence of a new model of electricity interaction among neighboring countries.

Traditionally, Bulgaria has maintained the position of a net electricity exporter in Southeast Europe, supported by a substantial share of baseload generation capacity and its strategic geographical location. Historically, the generation capabilities of the national power system have provided stable opportunities for regional electricity exports, making cross-border electricity exchange a long-established component of system operation.

However, the analysis of the period 2019–2025 indicates a gradual transition toward a more complex operational framework, in which cross-border electricity flows no longer serve exclusively as a mechanism for commercial electricity trading but increasingly function as an instrument for regional power system balancing and operational flexibility.

Impact of Renewable Energy Sources on Regional Electricity Flows

The increasing penetration of photovoltaic generation has significantly altered the profile of cross-border electricity exchange.

During periods of high solar generation, temporary electricity surpluses are created, which may be utilized through:

- regional electricity exchange;
- energy storage technologies;
- renewable generation curtailment;
- flexible demand-side management.

Conversely, during evening hours, when photovoltaic generation rapidly decreases, the need for electricity imports or fast-response balancing resources increases substantially.

These developments are shaping a new electricity architecture in which interconnection corridors progressively evolve from conventional transmission assets into strategic instruments for regional balancing and system flexibility.

As renewable energy penetration continues to increase, cross-border interconnections increasingly operate as distributed balancing resources, enabling the transfer of surplus electricity between interconnected markets and contributing to the stabilization of regional power systems.

Transition Toward an Adaptive Operational Model

The analysis reveals a gradual transition from the conventional electricity system paradigm (Figure 4), characterized by centralized generation and predictable power flows, toward an adaptive operational model (Figure 5) in which electricity generation, demand, storage, and cross-border exchange are dynamically coordinated.



Figure 4 Conventional Power System Management Model

Under this emerging framework, the operational value of electricity is determined not only by the quantity of energy generated but also by the capability of the system to provide flexibility, balancing services, and rapid adaptation to changing generation and demand conditions. Consequently, the strategic importance of forecasting, storage technologies, and regional electricity exchange continues to increase, becoming essential elements of modern power system operation.



Figure 5 Adaptive Power System Architecture Based on the On-Demand Energy Integration (ODEI) Concept

This transformation constitutes one of the fundamental engineering prerequisites for the successful integration of high shares of renewable energy sources, enabling power systems to maintain operational stability, flexibility, and reliability under increasingly variable generation conditions.

V. Conceptual Model for Adaptive Renewable Energy Integration: On-Demand Energy Integration (ODEI)

The increasing penetration of renewable energy sources necessitates the development of new engineering approaches for power system management. Conventional operational models, based on centralized generation and predictable demand patterns, are gradually becoming insufficient under conditions of high variability in renewable generation.

Modern power systems require a transition toward an adaptive architecture in which generation, energy storage, forecasting mechanisms, and regional electricity exchange operate as an interconnected and dynamic environment.

Within the framework of this study, a conceptual On-Demand Energy Integration (ODEI) model is proposed to support the operation of power systems with high levels of renewable energy integration.

The proposed model is structured into six sequential functional layers.

5.1 Generation Layer

The first layer encompasses all electricity generation assets, including:

- photovoltaic power plants;
- wind power plants;
- hydropower plants;
- nuclear generation facilities;
- conventional baseload generation units.

The primary function of this layer is to provide electricity generation and supply operational data to the forecasting module.

Under conditions of high renewable energy penetration, the critical parameter is no longer solely the quantity of electricity generated but also the predictability of the generation profile.

5.2 Forecast Layer

The second layer is responsible for forecasting:

- electricity generation;
- electricity demand;
- market price signals;
- cross-border network loading;
- the probability of deficit operating conditions.

The forecasting framework is expected to utilize:

- machine learning techniques;
- statistical forecasting models;
- short-term prediction algorithms;
- historical operational datasets.

The engineering rationale behind this layer is to minimize deviations between forecasted and actual system behavior.

5.3 Storage Layer

The Storage Layer performs the function of mitigating generation variability through the utilization of:

- pumped-storage hydropower plants (PSHPPs);
- battery energy storage systems (BESS);
- hybrid energy storage solutions;
- future hydrogen-based energy storage technologies.

The primary objective of this layer is to absorb excess electricity during periods of surplus generation and provide balancing support during periods of increased demand or reduced renewable output.

5.4 Regional Exchange and Market Integration Layer

The next layer incorporates:

- cross-border electricity exchange;
- market coupling mechanisms;
- balancing markets;

optimization of interconnection capacity utilization.

Within the proposed framework, electricity exchange no longer serves solely as a reserve mechanism but evolves into an active instrument for power system management and operational flexibility.

The increasing level of interconnection across Europe, combined with enhanced coordination among transmission system operators, represents a key factor for the sustainable operation of modern power systems.

5.5 Adaptive Control Layer

The final operational layer is responsible for:

- automated decision-making processes;
- demand-side management;
- congestion mitigation;
- maintenance of system resilience;
- management of balancing and reserve resources.

This layer functions as the central decision-making component of the ODEI architecture, coordinating information flows and operational actions across all preceding layers.

5.6 Engineering Application Potential within the Bulgarian Power System

The implementation of the ODEI model within the Bulgarian power system creates opportunities for:

- enhancing overall system resilience;
- reducing renewable energy curtailment;
- improving the efficiency of cross-border electricity exchange;
- increasing forecasting accuracy;
- optimizing the utilization of system reserve resources.

The proposed approach considers the power system not as a collection of individual generation assets but as an integrated and dynamic operational environment capable of adaptive behavior under conditions of accelerated energy transition and increasing renewable energy penetration [18–20].

This transformation represents one of the fundamental engineering prerequisites for the successful integration of high shares of renewable energy sources while maintaining operational stability, flexibility, and security of electricity supply.

VI. Conclusions

This study examined the impact of the accelerated deployment of renewable energy sources on the operation of the Bulgarian power system under conditions of a changing model of regional electricity interaction. The analysis demonstrates that the contemporary electricity sector is undergoing a profound structural transformation driven by the combined influence of technological, market, and infrastructure-related factors.

The increasing penetration of renewable energy sources contributes significantly to the decarbonization of the electricity sector; however, it simultaneously increases the complexity of power system operation and balancing. The variable nature of renewable generation necessitates the development of more flexible approaches to system management, forecasting, and regional coordination [21–23].

The obtained results indicate that the role of cross-border electricity exchange is gradually evolving. Interconnection corridors no longer function solely as reserve mechanisms for ensuring security of supply but are

increasingly acquiring the characteristics of active instruments for regional power system balancing and operational flexibility.

The conducted analysis allows the following key conclusions to be formulated:

1. Renewable Energy Sources Are Transforming the Conventional Power System Management Paradigm

The traditional principle of adapting generation to electricity demand is gradually being replaced by an operational framework in which system flexibility, forecasting capabilities, and regional electricity exchange become determining factors for maintaining system stability.

2. Interconnection Capacity Is Becoming a Key Instrument for Power System Resilience

The development of cross-border interconnections and enhanced coordination among transmission system operators create opportunities for reducing system imbalances and improving the resilience of electricity markets. As electricity flows become increasingly variable, regional coordination assumes a progressively more important role in maintaining secure system operation.

3. Energy Storage Systems Are Emerging as a Structural Component of Modern Power Systems

The further development of pumped-storage hydropower plants, battery energy storage systems, and future energy storage technologies will represent a critical prerequisite for the effective integration of high shares of renewable generation.

4. Regional Integration Enhances Power System Adaptability

The expansion of European market mechanisms, coordinated operational management, and digitalization creates conditions for achieving higher levels of operational resilience and adaptive system performance.

5. A Transition Toward Adaptive Management Frameworks Is Required

The proposed On-Demand Energy Integration (ODEI) model demonstrates the potential for establishing an engineering framework that integrates forecasting, energy storage, cross-border electricity exchange, and system management within a unified operational environment.

The scientific contribution of this study lies in the development of an integrated systems-engineering approach for assessing the impact of renewable energy sources on power system operation through the combined evaluation of generation indicators, cross-border electricity flows, and adaptive management mechanisms.

The results indicate that the future development of the electricity sector will be determined not only by the amount of installed renewable generation capacity but also by the ability of power systems to provide flexibility, resilience, and a high degree of operational coordination.

Under conditions of accelerated energy transition, Bulgaria possesses strategic prerequisites for the development of a modernized electricity infrastructure capable of operating as an integrated regional energy participant within the broader European electricity architecture.

Ultimately, the successful integration of large-scale renewable energy sources will depend on the ability of power systems to evolve from conventional generation-oriented structures toward adaptive, data-driven, and flexibility-oriented operational architectures capable of responding effectively to increasingly dynamic energy environments.

References:

1. Seljak, T., Baleta, J., & Mikulčić, H. (2022). Integration of energy systems, circular economy and efficiency measures. Cleaner Chemical Engineering.
2. Grbić, Maja & Pavlovic, Aleksandar. (2024). ANALYSIS OF MAGNETIC FLUX DENSITY LEVELS IN THE INCREASED SENSITIVITY AREAS LOCATED ABOVE THE 10/0.4 kV SUBSTATIONS. I-1.17. 10.46793/CIRED24.I-1.17MG.
3. Hansson Mild, Kjell & Mattsson, Mats-Olof & Jeschke, Peter & Israel, Michel & Ivanova, Michaela & Shalamanova, Tsvetelina. (2023). Occupational Exposure to Electromagnetic Fields—Different from General Public Exposure and Laboratory Studies. International Journal of Environmental Research and Public Health. 20. 6552. 10.3390/ijerph20166552.
4. Ivanova, Michaela & Israel, Michel & Shalamanova, Tsvetelina & Zaryabova, Victoria. (2023). Problems with the implementation of the European legislation for the protection from laser radiation in the working environment. 10.21175/rad.abstr.book.2023.25.4.
5. Angelov Plamen, Simulation of a Small Pv System Installed In An Urban Area, 15th National Conference with International Participation, ELECTRONICA 2024 – Proceedings Conference Paper 2024 DOI: 10.1109/ELECTRONICA63645.2024.11146066, ISBN 979-835039039-1
6. Angelov Plamen, Small Solar System Design, Polynomial Transfer Function Derivation - Part 1 15th National Conference with International Participation, ELECTRONICA 2024 – Proceedings Conference Paper 2024, DOI: 10.1109/ELECTRONICA 63645.2024.11146125, ISBN 979-835039039-1

7. M. Matsankov, "Study of the Voltage Levels in the Nodes of A Single-Loop Network with Connected Renewable Decentralized Energy Sources," 2024 6th International Conference on Power and Energy Technology (ICPET), Beijing, China, 2024, pp. 154-158, doi: 10.1109/ICPET62369.2024.10940667.
8. Zaerov, E., Letskovska, S., Seymenliyski, K., Simionov, R., PV SYSTEM MONITORING BY IOT IN SMART UNIVERSITY, ICTRS '20, October 5–6, 2020, Milan, Italy, ISBN: 978-1-4503-7730-0 pp. 44-49
9. Seymenliyski K., D, Radostin, S., Dolchinkov, Radoslav, R., Simionov, Application of European Union directives on energy efficiency of building systems in practical training of students in RES technologies ICTRS ’21, p. 43-47, November 15, 16, 2021, ACM ISBN 978-1-4503-9018-7/21
10. Daniela MAREVA, Dimitar YUDOV, Emil MAREV, Electronic transformer for a small photovoltaic plant, SIELA 28-30 May 2012, XVII-th International Symposium on Electrical Apparatus and Technologies,Bourgas, Bulgaria, volume 1, pp.210-217, ISSN:1314-6297
11. Matsankov M, St. Petrov, Modeling of the induced voltage in a disconnected grounded conductor of a three-phase power line, International Conference on Smart City and Green Energy (ICSCGE 2021) November, ISBN: 978-1-6654-1425-8, DOI 10.1109/ICSCGE53744.2021.9654332
12. T. Kostadinov, Simeonov, S., Atanassova, V., Sotirova, E., Simeonova, N., “Generalized net of a centralized embedded system”, Advances in Intelligent Systems and Computing, Proceedings, Springer International Publishing Switzerland, vol 559, pp. 299-304, ISSN: 2194-5357
13. P. Angelov, Theoretical and practical training using the software with integrated circuit models - part 2, International Scientific Conference "The Black Sea - Doors and Bridges”, 10-11 June 2022, BFU, Burgas, Bulgaria, 2022, pp. 566-568, ISBN-13: 978-619-253-017-4
14. Dolchinkov, R., Yovkov, A., Todorov, V., Ventsislavov, K. (2023). Integrated Platform for Vehicle Charging Based on Renewable Energy Resources. In: Shishkov, B., Lazarov, A. (eds) Telecommunications and Remote Sensing. ICTRS 2023. Communications in Computer and Information Science, vol 1990. Springer, Cham. https://doi.org/10.1007/978-3-031-49263-1_7
15. G. Dobrev, M. Matsankov, N. Paunkov and D. Budakova, "Determination of Photocell Efficiency," 2024 9th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE), Ruse, Bulgaria, 2024, pp. 1-4, doi: 10.1109/EEAE60309.2024.10600566.
16. Letskovska, S., Zaerov, E., Seymenliyski, K., Mikhov, S., Environmental Influence On Renewable Sources Productivity, International Conference on High Technology for Sustainable Development (HiTech 2018), Proceedings, 2018, 8566343 Sofia, Bulgaria 11-14 June 2018, IEEE Catalog Number: ISBN: 978-1-5386-7040-8, pp.209-212

17. Seymenliyski, K., Zaerov, E., Simionov, R., Letskovska, S. Reducing The Environmental Impact Of Electrical Installations, International Conference on High Technology for Sustainable Development (HiTech 2018) Sofia, Bulgaria 11-14 June 2018, Proceedings, 2018, 8566396 IEEE Catalog Number: ISBN: 978-1-5386-7040-8, pp.206-209
18. Ivanova, M. Responsibility of the state for damages caused to citizens in the criminal process, and the mechanisms for support and financial compensation for victims of crimes", Burgas, 2018 Pp. 214, ISBN 978-619-7125-44-2, Publisher: FLAT-Burgas
19. Daniela Mareva "ELECTROMAGNETIC COMPATIBILITY IN POWER TRANSISTOR CONVERSION DEVICES", International Scientific conference "Multidisciplinary innovations for social change: educational transformations and entrepreneurship", Burgas Free University, 2024, pp. 642-647, ISBN 978-619-253-038-9
20. Daniela Mareva „Integrating solar energy into its storage systems - part 1"BFU Yearbook, Volume L, BURGAS 2024г., p.237-243, ISSN: 1311-221X
21. Radoslav Simionov, Kamen Seymenliyski, Radostin Dolchinkov, Silvia Letskovska, Ginko Georgiev, Eldar Zaerov, Atanas Yovkov, Studying the Impact of PV Plants on Power Quality, Telecommunications and Remote Sensing, 11th International Conference, ICTRS 2022, Sofia, Bulgaria, November 21–22, 2022, Proceedings, Pages 72-84, Softcover ISBN 978-3-031-23225-1 eBook ISBN 978-3-031-23226-8, DOI https://doi.org/10.1007/978-3-031-23226-8 SCOPUS
22. Galina Baycheva, Radostin Dolchinkov, Silvia Letskovska, Kamen Seimenliyski, Radoslav Simionov, Velizar Todorov, IMPACT OF CLIMATE CHANGE AND NATURAL DISASTERS ON THE PRODUCTION OF ENERGY FROM RENEWABLE ENERGY SOURCES, Burgas 2024, BFU Yearbook, Volume L, ISSN: 1311-221X, pp. 410 – 421
23. Radostin Dolchinkov, Kamen Seimenliyski, Hristo Mihaylov, SAFE FUNCTIONING OF ENERGY SYSTEMS UNDER SCADA CONTROL, BSU 2024, "Multidisciplinary Innovations for Social Change: Educational Transformations and Entrepreneurship", ISBN: 978-619-253-038-9, p. 610 - 621

TRANSFORMATION OF BULGARIA FROM AN ENERGY EXPORTER TO A REGIONAL ENERGY COORDINATION HUB: THE ROLE OF RENEWABLE ENERGY SOURCES, MARKET INTEGRATION AND GEOPOLITICAL FACTORS

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Abstract: *This study examines the transformation of Bulgaria's role within the regional electricity architecture under conditions of accelerated renewable energy deployment, deepening European market integration, and increasing dynamics of cross-border electricity exchange. The analysis investigates the processes leading to a gradual transition from the traditional role of a net electricity exporter toward a regional coordination and transit hub within Southeast Europe. Particular attention is devoted to the impact of asynchronous renewable energy generation patterns across interconnected regional markets and the growing need for predictive management of cross-border electricity flows. The study evaluates the role of interconnection capacity, market integration mechanisms, and regional transmission infrastructure in enhancing power system resilience and operational efficiency. A conceptual Regional Energy Routing and Regulation (RER) model is proposed, based on predictive analysis of regional generation and demand patterns, assessment of cross-border transmission capacity, and optimization of electricity transit flows among interconnected power systems. The proposed framework considers Bulgaria as an adaptive regional coordination mechanism for managing electricity corridors and optimizing cross-border energy exchange under conditions of high renewable generation variability. The proposed approach does not duplicate the functions of ENTSO-E or transmission system operators. Instead, it represents an additional regional framework for predictive coordination and optimization of electricity flows among interconnected national markets. The scientific contribution of the study lies in the development of a conceptual framework for predictive regional electricity transit management and cross-border energy exchange coordination in Southeast Europe. Through the analysis of electricity flows, market mechanisms, and regulatory developments, the study identifies the structural transition from a conventional export-oriented model toward a dynamic framework based on regional balancing,*

transit optimization, and coordinated electricity exchange. The results indicate that Bulgaria is gradually strengthening its position as a strategic regional energy coordination hub within the Balkan region. Future development of this model will depend on the level of digitalization, the deployment of advanced forecasting tools, the expansion of electricity storage technologies, and the ability of regional markets to respond effectively to evolving geopolitical risks in the energy sector.

Keywords: *Regional Energy Coordination, Cross-Border Electricity Exchange, Energy Corridors, Market Coupling, ENTSO-E, Electricity Transit Optimization, Regional Energy Routing and Regulation (RER), Predictive Energy Management*

I. Introduction

The European electricity sector is undergoing an accelerated structural transformation driven by decarbonization policies, the rapid deployment of renewable energy sources (RES), the digitalization of energy markets, and the deepening integration of national electricity systems. As the share of renewable generation continues to increase, the ability to coordinate cross-border electricity flows and optimize the utilization of regional transmission infrastructure is becoming increasingly important [1,2].

Over the past decade, the traditional paradigm of power system operation, largely based on local generation and national electricity balancing, has gradually evolved toward a more interconnected regional framework. The growing penetration of renewable energy sources has led to the emergence of asynchronous generation patterns among neighboring countries, resulting from differences in meteorological conditions, generation portfolios, and local demand dynamics [1–3].

As a consequence, temporary electricity surpluses may arise in one region while neighboring power systems experience deficits in renewable generation. These developments create a growing need for enhanced coordination of cross-border electricity exchange and provide the foundation for adaptive regional mechanisms capable of managing electricity flows across interconnected markets [4–7].

Within this context, the Republic of Bulgaria occupies a strategic position within the electricity architecture of Southeast Europe due to the combination of:

- a geographical location connecting northern and southern energy corridors;

- a well-developed transmission infrastructure;
- extensive interconnection capacity with neighboring countries;
- a traditionally strong generation base;
- participation in the integrated European electricity market.

Historically, the Bulgarian power system has functioned primarily as a net electricity exporter within the region. The country's generation portfolio, consisting of nuclear power generation, thermal power plants, hydropower facilities, and an increasing share of renewable energy sources, has provided stable opportunities for regional electricity exports and contributed significantly to the regional electricity balance.

However, the ongoing integration of European electricity markets, the expansion of cross-border coordination mechanisms, the increasing variability of renewable generation, and the dynamics of international energy prices are gradually transforming this traditional model [8–12].

Under these conditions, the role of transmission infrastructure is evolving beyond its conventional technical function and is increasingly acquiring strategic geo-energy significance. Electricity corridors are becoming critical instruments for balancing regional electricity markets and enhancing the resilience of interconnected power systems.

Consequently, Bulgaria is gradually acquiring the characteristics of a regional electricity coordinator, where system value is determined not solely by the volume of electricity produced and exported but also by the ability to facilitate, coordinate, and optimize cross-border electricity flows within a broader regional framework.

The present study aims to analyze the transformation of the Bulgarian electricity sector during the period 2015–2025 through an assessment of the impact of renewable energy sources, European market integration, and geopolitical factors on the country's evolving regional role [13–15].

The scientific novelty of the study lies in the development of a conceptual framework describing the transition from a traditional net electricity exporter toward a Regional Energy Regulator (RER) model based on the interaction between generation resources, market integration mechanisms, and cross-border electricity coordination. The proposed framework examines the potential role of Bulgaria as an adaptive regional coordination hub capable of supporting the efficient management of electricity corridors and optimizing electricity exchange among interconnected markets in Southeast Europe.

II. Methodology

This study applies an integrated analytical approach to evaluate the transformation of Bulgaria's role within the regional electricity architecture under conditions of accelerated market integration and increasing dynamics of cross-border electricity exchange (Table 1).

The methodological framework combines:

- analysis of regional electricity flows;
- assessment of interconnection capacity and cross-border connectivity;
- comparative analysis of regional electricity markets;
- evaluation of market integration processes within the ENTSO-E framework;
- assessment of geopolitical factors;
- conceptual modeling of predictive electricity transit coordination.

The study covers the period 2015–2025, enabling the investigation of the transformation of the regional electricity model before and after the accelerated deployment of renewable energy sources and the intensified integration of European electricity markets.

The primary objective of the methodological approach is to identify the conditions and drivers supporting the development of Bulgaria as a regional energy coordination and transit hub in Southeast Europe.

2.1 Analysis of Regional Electricity Exchange

A comparative assessment was conducted of:

- cross-border electricity exchange;
- changes in the net electricity balance;
- the dynamics of regional electricity flows;
- the role of interconnection infrastructure;
- the development of regional electricity corridors.

The main objective of this analysis is to examine the evolving role of Bulgaria within the regional electricity system and to evaluate its potential to develop a coordination function under conditions of increasing cross-border integration.

2.2 Analysis of European Market Integration

The study includes an assessment of:

- market coupling mechanisms;
- the development of regional electricity markets;
- coordination among transmission system operators (TSOs);
- the role of ENTSO-E;
- the evolution of cross-border exchange mechanisms.

Particular attention is devoted to the influence of European market integration on the transformation of electricity exchange from a model primarily based on national markets toward a coordinated regional electricity exchange framework.

2.3 Analysis of Geopolitical Factors

The study further examines external factors with the potential to influence the regional electricity architecture, including:

- regional energy interdependencies;
- geopolitical instability;
- diversification of energy flows;
- development of strategic infrastructure;
- regional energy security;
- the impact of European regulatory mechanisms.

The primary objective of this analysis is to evaluate the influence of the geopolitical environment on the development of cross-border electricity exchange and the resilience of the regional electricity system.

Table 1 *Methodological Framework of the Study*

Research Direction	Primary Focus	Expected Research Outcome
Regional Electricity Exchange	Cross-border electricity flows and electricity corridors	Identification of Bulgaria's evolving regional role
European Market Integration	Market coupling mechanisms and ENTSO-E coordination	Assessment of regional market integration processes
Geopolitical Factors	Energy security and regional interdependencies	Evaluation of strategic resilience and system robustness
RER Model	Predictive electricity transit management	Development of a conceptual framework for regional electricity coordination

2.4 Conceptual Modeling of the Regional Energy Regulator (RER)

As part of the study, a conceptual **Regional Energy Regulator (RER)** model was developed based on:

- predictive analysis of regional generation patterns;
- identification of regions with anticipated energy deficits;
- assessment of regions with potential generation surpluses;
- evaluation of cross-border interconnection capacity;
- optimization of electricity transit routes;
- coordination of regional electricity corridors.

The proposed model considers Bulgaria as an adaptive regional coordination mechanism for managing cross-border electricity exchange among interconnected power systems in Southeast Europe.

The conceptual framework is designed to support the predictive coordination of regional electricity flows by integrating information on generation availability, demand patterns, transmission capacity, and regional market conditions. Through the identification of deficit and surplus regions, the model enables the evaluation of alternative electricity transit routes and the optimization of electricity exchange across interconnected markets.

Unlike traditional approaches focused primarily on national electricity balances, the RER model adopts a regional perspective in which electricity corridors, interconnection capacity, and market integration mechanisms constitute key elements of system coordination. The framework therefore provides a basis for enhancing regional electricity system resilience and improving the utilization of existing transmission infrastructure under conditions of increasing renewable energy penetration and growing variability of cross-border electricity flows.

III. Evolution of Bulgaria's Role in Regional Electricity Exchange

The Bulgarian power system has traditionally occupied a strategic position within Southeast Europe due to the combination of substantial generation capacity, a well-developed transmission infrastructure, and a favorable geographical location connecting the northern and southern energy corridors of the region [16–18].

Historically, the national electricity sector has operated primarily as a net electricity exporter, supported by the availability of reliable baseload generation capacity and the ability to maintain stable cross-border electricity exchange with neighboring countries. Over time, electricity exports became a key component of the regional electricity balance and an important contributor to energy security and system stability across the Balkan region [19, 20].

During the period 2015–2025, however, significant changes began to emerge in the regional electricity landscape. The rapid deployment of renewable energy sources, the acceleration of European market integration, and the increasing interconnectivity among national power systems have gradually transformed the traditional model of electricity exchange [21–23].

Under conditions of increasing renewable energy penetration, electricity flows are no longer determined solely by the availability of generation capacity. Instead, they are increasingly influenced by short-term variations in meteorological conditions, market price signals, and fluctuations in regional electricity demand.

These developments have led to the emergence of asynchronous generation patterns among neighboring countries. During certain periods, one power system may experience temporary generation surpluses, while adjacent markets simultaneously face shortages of renewable generation. As a result, the importance of cross-border electricity exchange as a mechanism for regional coordination and resource optimization continues to increase [24,25].

Owing to its well-developed transmission infrastructure and extensive interconnection capacity, Bulgaria is gradually acquiring the characteristics of a regional electricity transit hub, facilitating the transfer of electricity flows among interconnected markets in Southeast Europe.

Within this evolving environment, the role of the country is progressively shifting from a model primarily based on direct electricity exports toward a more advanced function centered on the coordination and optimization of regional electricity exchange [26,27].

The ongoing development of cross-border coordination mechanisms and electricity flow management frameworks further increases the strategic importance of interconnection infrastructure and enhances the role of adaptive management of regional electricity corridors. Consequently, the value of the Bulgarian electricity system is increasingly determined not only by its generation capacity but also by its ability to facilitate efficient electricity transit, support regional balancing, and contribute to the stability of interconnected electricity markets.

This transition represents one of the key structural changes currently taking place within the Southeast European electricity architecture and provides the foundation for the development of new regional coordination mechanisms capable of supporting the growing complexity of cross-border electricity exchange.

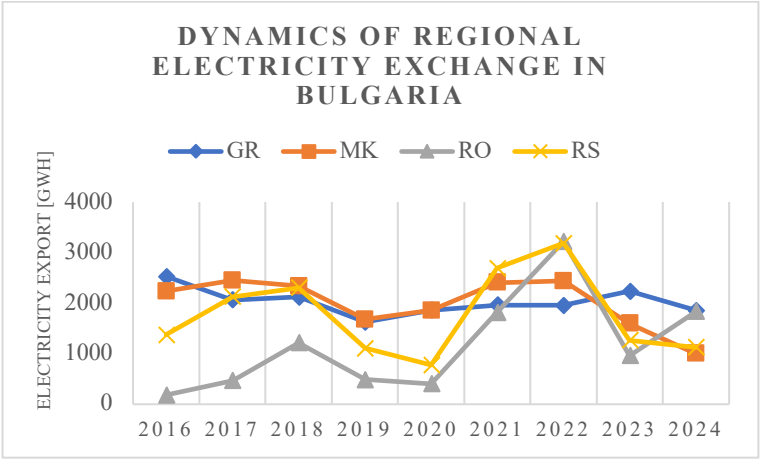


Figure 1 *Regional Electricity Exchange*

The analysis of cross-border electricity exchange reveals significant dynamics in regional electricity flows during the period 2016–2024 (Figure 1). Substantial changes can be observed in the direction and intensity of electricity exports, particularly during the period following 2020–2022, which was characterized by accelerated market integration and increased volatility in regional electricity markets.

The data indicate a growing importance of interconnection capacity and cross-border electricity exchange as instruments for regional electricity coordination. The observed changes in electricity flow patterns confirm the ongoing transition of Bulgaria's role from that of a traditional electricity exporter toward an adaptive regional transit and coordination hub within the Southeast European electricity market.

The results further suggest that cross-border electricity exchange is increasingly evolving beyond its conventional commercial function and is becoming an essential mechanism for balancing regional electricity systems under conditions of growing renewable energy penetration. Asynchronous renewable generation patterns across neighboring countries create opportunities for more efficient utilization of regional transmission infrastructure and strengthen the strategic importance of electricity corridors in maintaining system stability and market efficiency.

Consequently, the value of Bulgaria's electricity infrastructure is progressively determined not only by its generation capacity but also by its ability to facilitate electricity transit, support regional balancing processes, and enhance the operational resilience of interconnected electricity markets.

IV. European Market Integration, ENTSO-E and the Geopolitical Context

The development of the European electricity sector over the past decade has been characterized by accelerated market integration, enhanced cross-border coordination, and the gradual establishment of a pan-European framework for electricity exchange management. Under conditions of increasing renewable energy penetration, the ability to efficiently manage cross-border electricity flows and optimize the utilization of interconnection capacity has become increasingly important.

The expansion of market coupling mechanisms and the growing coordination among transmission system operators are progressively transforming the traditional operating model of national electricity markets. Electricity exchange is increasingly influenced by regional market dynamics, real-time generation patterns, and the availability of cross-border transmission capacity.

Within this context, the role of ENTSO-E has become essential for the coordinated and secure operation of the European electricity system. The organization provides the framework for:

- synchronization among transmission system operators;
- coordination of cross-border electricity exchange;
- management of interconnection capacity;
- development of integrated European electricity markets;
- enhancement of electricity system security and reliability.

The development of integrated European electricity markets and increasing cross-border coordination creates conditions for a higher degree of regional interdependence among the countries of Southeast Europe.

The proposed Regional Energy Regulator (RER) model does not duplicate the functions of ENTSO-E or transmission system operators. Instead, it represents an additional regional framework for the predictive coordination and optimization of cross-border electricity flows under conditions of increasing market complexity and growing renewable energy penetration.

While ENTSO-E provides the pan-European framework for synchronization, coordination, and interconnection capacity management, the proposed RER model is focused on the regional level and aims to support the analysis and optimization of electricity transit flows among interconnected power systems.

The core concept of the model is based on the predictive identification of regions with anticipated electricity deficits and regions with potential generation surpluses, combined with the optimization of electricity transit

corridors between them. In this way, the model supports the efficient utilization of regional transmission infrastructure and enhances the adaptability of cross-border electricity exchange mechanisms.

4.1 Geopolitical Context and Regional Energy Corridors

Geopolitical developments in recent years have significantly increased the importance of regional electricity interconnectivity and the resilience of cross-border infrastructure. Energy security is gradually becoming a critical factor for the stability of European economies, while the development of regional electricity corridors is acquiring increasing strategic importance.

Southeast Europe occupies a particularly important position within this framework due to its location between northern, Black Sea, and southern energy corridors. Within this context, Bulgaria functions as a natural electricity transit corridor connecting multiple regional electricity markets.

The existence of extensive interconnection capacity with neighboring countries, combined with participation in the integrated European electricity market, creates favorable conditions for a higher level of regional electricity exchange coordination.

Under conditions of highly variable renewable generation and increasing volatility in energy markets, the ability to predict, coordinate, and optimize cross-border electricity flows among regional corridors is becoming increasingly important.

Regional electricity interconnectivity is also gaining significance in the context of European energy security, particularly in response to dynamic geopolitical developments and the need for diversification of energy flows. Consequently, the development of resilient electricity corridors across Southeast Europe is gradually emerging as a strategic factor for the stability, reliability, and efficiency of regional electricity markets.

In this evolving environment, the strategic value of Bulgaria is increasingly determined not only by its generation capabilities but also by its ability to facilitate regional electricity transit, support cross-border coordination, and contribute to the resilience of the interconnected European electricity system.

V. Conceptual Model of the Regional Energy Regulator (RER)

Under conditions of accelerated European electricity market integration and increasing dynamics of cross-border electricity exchange, the need emerges for regional mechanisms capable of supporting the predictive coordination of electricity flows among interconnected power systems.

Within the framework of this study, a conceptual Regional Energy Regulator (RER) model is proposed, in which Bulgaria operates as an adaptive regional coordination and transit hub for the analysis, optimization, and management of cross-border electricity exchange in Southeast Europe.

The core concept of the model is based on the integration of regional data related to electricity generation, demand, interconnection capacity, and market conditions in order to support the predictive identification of:

- regions with anticipated electricity deficits;
- regions with forecasted generation surpluses;
- optimal electricity corridors;
- opportunities for electricity transit;
- potential infrastructure constraints.

The proposed approach does not duplicate the functions of ENTSO-E or transmission system operators. Instead, it represents an additional regional framework for the predictive management and optimization of electricity flows among interconnected national markets.

5.1 Integration Architecture of the RER Model

The proposed RER model is based on the integration of data from multiple regional sources in order to establish a predictive framework for the coordination of cross-border electricity exchange.

The principal input parameters include:

- meteorological data;
- forecasted renewable energy generation;
- regional electricity demand;
- interconnection capacity;
- technical parameters of transmission infrastructure;
- market price signals;
- regional electricity exchange data.

Meteorological information is utilized to forecast the expected generation profiles of renewable energy sources across regional markets. These data may be obtained from the national meteorological and hydrological institutes of the respective countries.

To assess generation patterns, the model utilizes historical generation data and cross-border electricity exchange information available through the ENTSO-E Transparency Platform.

Forecasts of regional electricity demand and analyses of interconnection capacity are based on information provided by national transmission system operators, together with technical data describing the characteristics and operational limits of cross-border interconnections.

The market module incorporates day-ahead and intraday price data obtained from regional electricity exchanges in order to support the optimization of electricity transit among interconnected markets.

Following the processing of the input parameters, the integrated RER framework evaluates potential deficit and surplus regions and determines feasible routes for coordinated cross-border electricity exchange.

The integration and synchronization of data originating from multiple regional sources enable the creation of a unified predictive environment for the analysis of cross-border electricity exchange and the identification of potential constraints within regional electricity corridors.

The proposed architecture provides a foundation for predictive electricity transit management by combining generation forecasting, demand assessment, transmission capacity evaluation, and market analysis within a single regional decision-support framework. In this manner, the model facilitates the proactive coordination of electricity flows and contributes to the efficient utilization of regional transmission infrastructure under conditions of increasing renewable energy variability.



Figure 2 *Integration Architecture of the Regional Energy Regulator (RER) Model*

Table 2 *Principal Input Data and Data Sources within the RER Framework*

Module	Primary Data	Potential Data Source
Meteorological Analysis	Temperature, cloud cover, wind speed, solar irradiation	National Meteorological and Hydrological Institutes
Renewable Generation Forecasting	Historical generation profiles	ENTSO-E Transparency Platform
Load Forecasting	National electricity demand	National Transmission System Operators (TSOs)
Interconnection Capacity Assessment	Technical parameters of interconnectors	ESO, Transelectrica, ADMIE, EMS
Market Analysis	Day-ahead and intraday electricity prices	IBEX, OPCOM, HENEX, SEEPEX
Routing Analysis	Regional electricity flows and network constraints	Integrated RER analysis

5.2 Architecture of the Predictive Routing Model

Following the completion of the forecasting process, the model coordinates regions with generation surpluses and regions experiencing anticipated electricity deficits through the selection of optimal routes for cross-border electricity exchange.

The routing framework operates through the identification of:

- regions with forecasted generation surpluses;
- regions with anticipated electricity deficits;
- potential electricity transit routes;
- interconnection constraints;
- market conditions affecting regional electricity exchange.

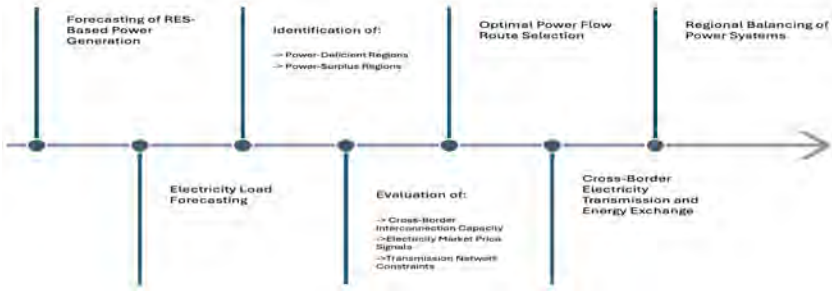


Figure 3 *Operational Algorithm of the Regional Energy Regulator (RER) Model*

The proposed routing framework is intended as a decision-support mechanism and does not perform operational dispatching or power system control functions, which remain under the responsibility of transmission system operators.

Following the analytical process, the system determines an optimal coordination strategy for electricity flows among interconnected regional electricity markets based on prevailing operating conditions.

The proposed framework represents a predictive approach for managing regional electricity exchange through the analysis of generation and demand patterns across interconnected power systems. The operational logic of the model is based on identifying regions with expected electricity deficits and regions with potential generation surpluses, followed by an assessment of interconnection capacity, market signals, and available electricity transit routes.

In this manner, the framework enables the coordinated redistribution of electricity flows among regional markets with the objective of enhancing regional power system resilience and optimizing the utilization of cross-border transmission infrastructure.

5.3 Operational Flow of the RER Model

The operation of the proposed Regional Energy Regulator (RER) model can be described as a sequence of interconnected analytical and decision-support stages.

Stage 1. Meteorological Analysis

Regional meteorological data are processed to forecast the expected operating conditions for renewable energy generation within individual countries.

Stage 2. Renewable Generation Assessment

Based on historical generation profiles and forecasted meteorological conditions, the expected renewable energy generation output is evaluated.

Stage 3. Regional Demand Analysis

A predictive assessment of electricity demand and regional load profiles is performed across interconnected electricity markets.

Stage 4. Interconnection Capacity Assessment

The model evaluates:

- available cross-border transmission capacity;
- technical operating constraints;
- loading conditions of interconnection assets;
- potential electricity corridors.

Stage 5. Market and Transit Analysis

The framework analyzes:

- electricity price signals;
- regional market conditions;
- potential electricity exchange routes;
- efficiency of available transit corridors.

Stage 6. Predictive Energy Routing

Following the integration and processing of all input parameters, the model determines an optimal routing strategy for coordinating electricity flows among interconnected regional markets.

Stage 7. Coordinated Cross-Border Exchange

Following route selection, coordinated electricity exchange is implemented with the objective of:

- reducing regional imbalances;
- optimizing the utilization of interconnection capacity;
- enhancing the resilience of the regional electricity architecture.

5.4 Bulgaria as a Regional Routing Hub

Within the proposed framework, Bulgaria functions as a regional transit and coordination hub connecting the northern and southern electricity corridors of Southeast Europe.

Due to its extensive interconnection infrastructure and strategic geographical location, the Bulgarian power system possesses the necessary

conditions to support the predictive coordination of electricity exchange among interconnected regional markets.

Under conditions of asynchronous renewable generation patterns, the proposed model enables the utilization of Bulgarian transmission infrastructure as an adaptive electricity transit corridor facilitating the transfer of electricity flows between regions with generation surpluses and regions experiencing electricity deficits.

Consequently, the role of Bulgaria gradually evolves from that of a traditional electricity exporter toward a regional coordination mechanism supporting the management and optimization of cross-border electricity exchange within Southeast Europe.

The proposed framework highlights the strategic potential of Bulgaria to operate not only as a producer and exporter of electricity but also as an intelligent regional coordination hub capable of enhancing electricity market integration, optimizing electricity transit, and strengthening the resilience of interconnected regional power systems.

VI. Conclusions

This study examined the transformation of Bulgaria's role within the regional electricity architecture under conditions of accelerated European market integration, increasing dynamics of cross-border electricity exchange, and growing penetration of renewable energy sources.

The conducted analysis demonstrates that contemporary electricity systems are gradually evolving from a model primarily based on local generation and national electricity balancing toward a regionally coordinated environment for managing electricity flows among interconnected markets.

Under conditions of asynchronous renewable generation patterns, the ability to predict, coordinate, and optimize cross-border electricity exchange is becoming increasingly important. The growing volatility of regional electricity markets and the increasing dependence on meteorological conditions create a need for adaptive mechanisms capable of coordinating electricity corridors across interconnected countries.

The results indicate that Bulgaria possesses strategic prerequisites for developing a function that extends beyond its traditional role as a net electricity exporter. The combination of a favorable geographical location, a well-developed transmission infrastructure, extensive interconnection capacity, and participation in the integrated European electricity market creates conditions for the development of a regional coordination role in managing cross-border electricity exchange throughout Southeast Europe.

Within the framework of the study, a conceptual Regional Energy Regulator (RER) model was proposed. The model is based on predictive analysis of generation and demand patterns, assessment of interconnection capacity, and optimization of electricity transit corridors among interconnected power systems.

The proposed framework does not duplicate the functions of ENTSO-E or transmission system operators. Instead, it represents an additional regional decision-support framework for the predictive coordination and optimization of electricity flows under conditions of increasing market complexity and renewable generation variability.

The principal scientific contribution of the study lies in the development of a conceptual architecture for predictive management of cross-border electricity exchange through:

- analysis of regional generation patterns;
- identification of deficit and surplus regions;
- assessment of interconnection capacity;
- optimization of electricity corridors;
- coordination of regional electricity transit flows.

The proposed approach creates opportunities for more efficient utilization of regional transmission infrastructure, reduction of electricity imbalances, and enhancement of the resilience of the regional electricity architecture during the ongoing energy transition.

The findings suggest that the future role of Bulgaria within Southeast Europe will be determined not only by its ability to generate and export electricity, but also by its capacity to facilitate, coordinate, and optimize electricity flows among interconnected regional markets.

In this context, the development of predictive frameworks for managing cross-border electricity exchange may become a key element for strengthening the resilience of the regional electricity architecture, improving the utilization of European transmission infrastructure, and supporting the secure integration of increasing shares of renewable energy sources within interconnected electricity systems.

Ultimately, the evolution from a traditional electricity exporter toward a regional coordination and routing hub represents a strategic opportunity for Bulgaria to strengthen its position within the emerging European electricity architecture and contribute to the long-term stability and efficiency of regional electricity markets.

References:

1. Strategic Vision for the Development of the Electricity Sector of the Republic of Bulgaria 2023 - 2053, Ministry of Energy of the Republic of Bulgaria
2. Strategy for Sustainable Energy Development of the Republic of Bulgaria until 2030, with a horizon until 2050 – Draft from 2021.,https://www.parliament.bg/pub/cW/
3. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_bg
4. https://www.consilium.europa.eu/bg/policies/green-deal/
5. Integrated Energy and Climate Plan of the Republic of Bulgaria 2021 - 2030, with a horizon until 2050.
6. https://ec.europa.eu/energy/sites/ener/files/documents/bg_final_necpmain_bg.pdf
7. https://dv.parliament.bg/DVWeb/showMaterialDV.jsp?idMat=147724
8. Radostin Dolchinkov, Atanas Yovkov, Velizar Todorov, Kristian Ventsislavov, Integrated platform for vehicle charging based on renewable energy resources, 12th International Conference, ICTRS 2023, Rhodes, Greece, September 18-19, 2023, Proceedings, ISBN 978-3-031-49262-4, eBook ISBN 978-3-031-49263-1
9. Silvia Letskovska, Milen Baltov, Kamen Seymenliyski, Radostin Dolchinkov, BLACK SEA – A RENEWABLE SOURCE OF ENERGY AND RESOURCES, BSU Yearbook, volume XLII, 2020, ISSN: 1311-221X, pp. 211 – 238
10. Kamen Seymenliyski, THE STRUCTURE OF PRODUCTION - A LEADING FACTOR FOR FORMING ELECTRICITY PRICES, BSU, 2021, vol. XLIV, pp. 116 - 126, ISSN: 1311-221X
11. Radostin Dolchinkov, SPECIFIC ASPECTS OF WIND GENERATORS. BSU Yearbook, volume XLII, 2020, ISSN: 1311-221X, pp. 80 – 10

HUMAN DIGITAL TWINS AND ETHICS

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Abstract: *Human Digital Twins (HDTs) are dynamic, data-driven computational representations of individuals that integrate physiological, behavioral, and cognitive data to simulate and predict human states and actions. HDTs are predictive and intervention-capable systems that can influence behavior through personalized feedback, optimization, and adaptive algorithms. Their capacity to model attention, preferences, and decision patterns creates risks related to autonomy erosion, manipulation, discrimination, and intensified surveillance. The paper analyzes the ethical implications of HDTs through the lenses of autonomy, identity, power asymmetry, and governance. It argues that HDTs represent a shift from data extraction to behavioral simulation, requiring new regulatory and ethical safeguards. Proactive governance grounded in transparency, proportionality, and digital self-determination is essential to ensure that human digital twins enhance human welfare rather than undermine cognitive and democratic autonomy.*

Keywords: *human digital twins, ethics*

Theoretical and Ethical Framework

The ethical analysis of Human Digital Twins (HDTs) requires an interdisciplinary framework that integrates insights from AI ethics, bioethics, and political economy. HDTs differ qualitatively from traditional digital profiling systems because they do not merely record past behavior; they simulate, predict, and potentially intervene in future human states and actions. This predictive and intervention-capable character introduces novel normative tensions that cannot be adequately addressed through conventional data protection paradigms alone.

Political Economy and Structural Power

Ethical evaluation must situate HDTs within broader socio-economic structures. HDTs do not exist in isolation; they are embedded in digital capitalism, platform ecosystems, and data-driven markets. HDTs depend on continuous data streams—wearables, smartphones, IoT systems, online platforms. This infrastructure expands surveillance capacity from episodic tracking to continuous behavioral modeling. The shift from data extraction

to behavioral simulation intensifies informational asymmetry. Institutions may gain predictive leverage over individuals, enabling anticipatory governance or behavioral monetization. Ethically, this raises concerns about concentration of predictive power, reduced informational self-determination, and institutional overreach.

Behavioral Data as Economic Capital

In digital markets, behavioral prediction becomes economically valuable. HDTs may enhance targeted advertising, dynamic pricing, and personalized persuasion strategies. When predictive accuracy is monetized, individuals risk becoming sources of behavioral surplus rather than autonomous agents. The economic incentive to maximize engagement may conflict with user well-being. This introduces a structural ethical tension between profit optimization and human dignity.

Cognitive Autonomy and Digital Self-Determination

This paper proposes cognitive autonomy as the central normative principle for evaluating Human Digital Twins. Cognitive autonomy refers to the preservation of independent mental processes free from covert behavioral manipulation or predictive domination. Because HDTs model attention, preferences, and intentions, they directly intersect with cognitive liberty. Digital self-determination in the HDT context includes awareness of simulation processes, control over data flows, right to inspect and contest predictive outputs, limits on behavioral steering, and transparent feedback mechanisms. Unlike traditional data rights, these protections address the predictive and intervention-capable nature of HDTs. No single ethical tradition sufficiently captures the complexity of Human Digital Twins. AI governance ensures procedural safeguards; bioethics protects dignity and autonomy; political economy exposes structural exploitation risks.Together, these dimensions enable a holistic ethical assessment of HDTs as transformative socio-technical infrastructures rather than mere data systems.

Ethical Challenges of Human Digital Twins

Human Digital Twins (HDTs) introduce a qualitatively new class of ethical risks because they do not merely store data about individuals but simulate, predict, and potentially intervene in their future states and behaviors. This predictive and intervention-capable architecture generates normative tensions that extend beyond conventional concerns about data privacy or algorithmic bias. The ethical challenges of HDTs emerge from their capacity to model cognition, anticipate decision-making, and shape behavioral outcomes within asymmetrical power environments.

There are five core ethical domains: (1) autonomy and behavioral manipulation, (2) privacy beyond data protection, (3) identity and ontological concerns, (4) discrimination and algorithmic inequality, and (5) exploitation within attention-driven markets.

1. Autonomy and Behavioral Manipulation

The central ethical concern surrounding HDTs is their capacity to influence the very behavior they predict. Unlike static digital profiles, HDTs operate in closed feedback loops: they collect behavioral data, generate predictive models, and adjust digital or physical environments accordingly. These adjustments—recommendations, nudges, alerts, risk signals—may alter the individual's subsequent decisions, which are then fed back into the system. This recursive architecture transforms HDTs from observational systems into behavioral steering mechanisms. The ethical problem is not prediction per se, but the instrumentalization of prediction for influence. When predictive outputs are used to optimize engagement, productivity, consumption, or compliance, the boundary between assistance and manipulation becomes blurred. Individuals may experience their decisions as self-determined while unknowingly operating within algorithmically constrained choice architectures.

Erosion of Cognitive Autonomy

Cognitive autonomy refers to the capacity to deliberate and decide without covert external control. HDTs threaten this autonomy in subtle but significant ways: personalized micro-targeting based on predicted emotional states, adaptive nudging calibrated to individual susceptibility, timing optimization to exploit attentional vulnerabilities, behavioral friction design that guides decision pathways. Such practices may not eliminate freedom outright but gradually narrow the field of perceived options. Over time, reliance on predictive feedback may externalize decision-making processes, leading to a form of algorithmic dependency. The ethical risk lies in the normalization of behavioral optimization as a default mode of interaction. When predictive systems continuously refine their capacity to anticipate and shape action, individuals risk becoming objects of behavioral engineering rather than autonomous subjects.

The Problem of Asymmetrical Predictive Knowledge

HDT operators may possess probabilistic insights into an individual's likely future behavior that exceed the individual's own conscious awareness. This asymmetry creates epistemic inequality: institutions can anticipate decisions before they are fully formed. Such predictive advantages may be used benevolently (e.g., early health intervention), but it may also be leveraged for commercial or political gain. The ethical concern arises

when individuals are denied access to, or understanding of, the predictive representations that shape their opportunities and environments. Autonomy requires not only freedom from coercion but also parity in informational power. HDTs disrupt this parity.

2. *Privacy Beyond Data Protection*

From Data Privacy to Inference Privacy

Traditional privacy frameworks focus on the protection of personal data collected and stored. HDTs complicate this model because much of their value lies not in raw data but in inferred insights—predicted health risks, purchasing intentions, emotional states, or cognitive traits. Inference privacy concerns the protection of predictive conclusions drawn from data, even if the original data were lawfully obtained. HDTs may generate highly sensitive insights about individuals that were never explicitly disclosed. For example, behavioral modeling may infer mental health vulnerabilities, risk tolerance levels, political inclinations, cognitive decline trajectories. Such inferences may affect access to insurance, employment, or credit without individuals ever being aware of their existence.

Continuous Monitoring and the Collapse of Context

HDTs often depend on real-time data streams from wearables, mobile devices, workplace sensors, or online platforms. This persistent monitoring collapses contextual boundaries between professional, private, and social domains. Contextual integrity—understood as the appropriate flow of information within defined social settings—is undermined when HDTs integrate cross-domain data into unified predictive models. A health metric may influence workplace evaluations; online browsing behavior may inform insurance risk scoring. The ethical challenge lies in preventing domain spillover effects that erode the separation of social spheres.

Predictive Permanence

Unlike transient data records, HDTs may maintain persistent longitudinal models that evolve over time. These models may outlive specific data inputs and continue generating predictions even after data deletion. This persistence creates what might be termed predictive permanence: the continued existence of a behavioral simulation independent of ongoing data generation. Ethical questions arise regarding the right to model deletion, the right to simulation suspension, the limits of predictive retention. Data protection alone does not address the lifecycle of behavioral simulations.

3. Identity and Ontological Concerns

The Twin as a Proxy Self

As HDTs increase in sophistication, they may serve as proxies in decision-making processes. Healthcare systems may rely on a twin's predicted responses to treatment; financial institutions may use behavioral models to assess reliability; employers may evaluate productivity forecasts. When institutional decisions are based on the twin rather than the individual's lived presence, the model begins to acquire quasi-representational authority. The twin becomes a functional stand-in for the person. This raises ontological concerns about representation fidelity, misalignment, and contestability. If the twin's predictions conflict with the individual's self-understanding, whose representation prevails?

Ownership and Control of the Digital Self

A core ethical question concerns ownership: Who controls the HDT? Is it a property of the individual, the platform, the employer, or the healthcare provider? If HDTs are treated as corporate assets, individuals may lose control over representations that profoundly shape their life chances. Ethical governance must clarify whether HDTs constitute extensions of personhood or commodifiable data constructs. Control rights over inspection, correction, portability, and deletion become central to preserving individual agency.

Posthumous and Persistent Twins

Advanced HDTs may persist beyond the individual's lifetime, particularly in healthcare research, legacy systems, or social simulations. Posthumous digital twins raise questions about dignity, consent continuity, and representation integrity. If predictive models continue to simulate a deceased individual's preferences or behaviors, ethical frameworks must address posthumous consent, legacy data governance, misuse of digital representations. The possibility of persistent simulation challenges conventional boundaries between life, data, and identity.

4. Discrimination and Algorithmic Inequality

Behavioral Risk Scoring

HDTs may generate behavioral risk assessments in domains such as health, insurance, employment, and finance. Even when technically accurate, such scoring systems may embed structural inequalities. Predictive models trained on historical data reflect existing disparities in income, access to care, and social opportunity. Without corrective intervention, HDTs risk entrenching these disparities under the appearance of objectivity.

Differential Surveillance

Not all individuals are equally subjected to predictive monitoring. Workplace HDTs may disproportionately track lower-income workers, while high-status individuals retain greater informational privacy. This asymmetry produces what might be termed stratified transparency: some populations become hyper-visible within predictive infrastructures, while others remain comparatively opaque. Justice requires careful evaluation of who bears the burden of continuous simulation and who benefits from predictive advantages.

Feedback Loops and Self-Fulfilling Prophecies

Predictive outputs may influence opportunities in ways that reinforce initial predictions. For example: a risk label may reduce access to credit, increasing financial instability; a productivity forecast may influence task allocation, shaping future performance; a health risk prediction may alter insurance premiums, limiting treatment options. Such feedback loops create self-fulfilling prophecies in which simulation shapes reality. Ethical governance must account for these recursive dynamics.

5. Exploitation in the Attention Economy

HDTs as Instruments of Behavioral Monetization

In digital markets, predictive accuracy translates directly into economic value. HDTs may refine targeted advertising, dynamic pricing, and engagement optimization by modeling attention patterns and cognitive vulnerabilities. When predictive systems optimize for engagement rather than well-being, they may systematically exploit attentional biases. The individual's cognitive resources become monetizable assets.

Commodification of Cognitive States

HDTs capable of modeling emotional fluctuations, stress levels, or decision fatigue enable unprecedented precision in persuasive timing. Such capabilities raise concerns about commodifying internal mental states. The ethical issue is not personalization alone but the extraction of economic value from cognitive processes without meaningful agency or compensation.

Structural Conflict of Interest

Platform operators deploying HDTs may face structural conflicts between profit maximization and user welfare. Behavioral steering designed to increase engagement may conflict with mental health or long-term well-being. Without regulatory intervention, market incentives may favor increasingly intrusive predictive systems. Ethical design must therefore address systemic incentive structures rather than isolated technical features.

Ethical Risks

The ethical challenges of Human Digital Twins converge around three risks:

• *Cognitive Domination* – erosion of independent decision-making through predictive steering.

• *Predictive Inequality* – asymmetrical access to and control over behavioral simulations.

• *Structural Exploitation* – monetization of human cognition within platform economies.

These risks extend beyond individual harm and can implicate democratic institutions, social equity, and human dignity. Given the multidimensional ethical challenges outlined above, traditional data protection approaches are insufficient. The next section therefore examines regulatory gaps and proposes governance mechanisms capable of addressing the predictive and intervention-capable nature of Human Digital Twins.

Governance and Regulatory Implications

The ethical challenges posed by Human Digital Twins (HDTs) cannot be adequately addressed through existing data protection regimes alone. HDTs represent a shift from data processing to behavioral simulation and predictive intervention. This shift requires a governance framework that moves beyond static notions of consent and data minimization toward dynamic oversight of predictive modeling, cognitive autonomy, and institutional power asymmetries.

This section analyzes the limits of current regulatory instruments, identifies structural governance gaps, and proposes a multi-layered model for responsible HDT governance.

Limits of Existing Legal Frameworks

Data Protection Law and Its Structural Boundaries

Contemporary data protection regimes focus primarily on lawful basis for data processing, consent requirements, purpose limitation, data minimization, right to access and deletion. While these principles remain essential, they are insufficient for HDTs for three primary reasons:

First, HDTs generate predictive inferences that may not qualify as raw personal data but nonetheless significantly affect individuals. Data protection law often regulates data collection but struggles to address downstream inferential modeling.

Second, consent becomes structurally weakened in HDT ecosystems. Continuous data aggregation, evolving model architectures, and emergent

predictive capabilities make it nearly impossible for individuals to fully understand the scope of future simulations at the moment of consent.

Third, data deletion does not necessarily eliminate predictive models trained on prior data. Even if raw data are erased, trained models may retain learned behavioral patterns, thereby limiting the practical effect of erasure rights.

Data protection frameworks were designed for data processing, not dynamic behavioral simulation.

Algorithmic Regulation and Risk-Based Approaches

Emerging AI regulations typically classify systems according to risk levels (e.g., high-risk vs. minimal-risk applications). HDTs may fall under high-risk categories when used in healthcare, employment, or public administration. However, risk-based classification faces several challenges: risk is dynamic rather than static, HDTs evolve through continuous data integration; contextual shifts may alter risk profiles without formal system redesign; behavioral harms (e.g., autonomy erosion) are difficult to quantify ex ante. Moreover, algorithmic regulation often focuses on fairness and discrimination but may underemphasize cognitive manipulation and predictive power asymmetry. A more nuanced governance model must incorporate autonomy-based risk metrics alongside harm-based evaluation.

Sectoral Fragmentation

HDT applications span multiple domains: Healthcare, Employment, Consumer platforms, Insurance, Smart cities. Each sector is governed by distinct regulatory frameworks. This fragmentation creates governance gaps when HDTs integrate cross-domain data. For example, health data may influence employment decisions, yet sectoral laws may not anticipate such integration. Effective governance requires cross-sector interoperability standards and harmonized oversight mechanisms.

Rethinking Consent in Predictive Environments

The Limits of Informed Consent

Informed consent presupposes that individuals understand the scope, purpose, and consequences of data processing. HDTs challenge this assumption because predictive capabilities evolve over time, new inferences may emerge from existing data, system interactions generate unforeseen behavioral insights. Consent becomes temporally unstable. What was acceptable at time of collection may later enable novel predictive uses. Thus, governance must move toward dynamic consent models, where individuals can continuously monitor and adjust permissions rather than provide one-time authorization.

The Right to Simulation Awareness

Because HDTs operate as predictive representations, individuals may be unaware of the existence or scope of their digital twin. A governance model should recognize a right to simulation awareness, ensuring that individuals are notified of the existence of a digital twin, informed about modeled domains (health, productivity, attention, etc.), made aware of predictive outputs influencing decisions. Without simulation awareness, consent is merely formal rather than substantive.

Contestability and Explanation

Individuals should have the right to inspect their digital twin representation, challenge inaccurate predictions, request correction of model outputs, demand human review in consequential decisions. Contestability must extend beyond data accuracy to predictive interpretation. Governance frameworks should require explainable model outputs in high-impact contexts.

Accountability in Distributed HDT Ecosystems

Allocating Responsibility

HDT infrastructures often involve multiple actors: Device manufacturers, Data aggregators, Model developers, Platform operators, Institutional users. This distributed architecture risks accountability dilution. Governance should establish clear responsibility allocation agreements, documentation of data flows, audit trails for predictive decisions, liability standards for predictive harm. Institutional responsibility must not be obscured by technical complexity.

Mandatory Impact Assessments

Behavioral simulation systems require ex ante evaluation similar to environmental or biomedical impact assessments. A Behavioral Impact Assessment (BIA) framework could require evaluation of autonomy risks, assessment of discriminatory impact, analysis of feedback loop dynamics, transparency documentation. Such assessments should be mandatory for high-risk HDT deployments.

Independent Auditing and Oversight

External oversight bodies should be empowered to conduct algorithmic audits, evaluate bias and fairness metrics, review predictive modeling assumptions, and monitor behavioral steering practices. Oversight institutions must possess technical expertise and enforcement authority to avoid regulatory capture.

Toward a Rights-Based Framework for Human Digital Twins

Given the limitations of existing governance mechanisms, a complementary rights-based approach may provide stronger normative grounding.

Right to Cognitive Autonomy

Individuals should be protected against covert behavioral manipulation. This includes prohibition of exploitative attention optimization, restrictions on subliminal persuasive design, transparency requirements for behavioral nudging. Cognitive autonomy should be recognized as a distinct dimension of digital rights.

Right to Twin Access and Portability

Individuals should have access to their digital twin model, portability across service providers, ability to export model data in interoperable formats. Portability reduces platform lock-in and mitigates power concentration.

Right to Twin Deletion and Suspension

Governance must clarify whether individuals can demand complete deletion of their twin, suspension of predictive modeling, temporal limitations on simulation persistence. Deletion rights must account for trained model artifacts rather than only raw data.

Right to Non-Discriminatory Prediction

Predictive outputs used in employment, insurance, or public services should meet strict anti-discrimination standards. This includes bias audits, fairness metrics, independent validation, and transparent evaluation criteria. Predictive accuracy alone does not justify discriminatory impact.

Institutional and Structural Safeguards

Ethical-by-Design Requirements

Regulators should mandate ethical-by-design principles in HDT development, including data minimization at modeling stage, clear model boundaries, built-in contestability features, user-facing transparency dashboards. Ethical safeguards must be embedded in system architecture rather than added post hoc.

Interoperability and Decentralization

Concentration of predictive infrastructure within dominant platforms amplifies power asymmetries. Governance should promote open standards, interoperability requirements, decentralized data architectures, federated modeling approaches. Reducing centralization limits systemic abuse.

Public Sector Deployment Standards

When HDTs are used in public governance — healthcare systems, welfare allocation, or smart city infrastructure — higher accountability standards must apply. Public deployments should require parliamentary or legislative oversight, public transparency reports, citizen participation mechanisms, independent review boards. Democratic legitimacy must accompany predictive governance.

International and Cross-Border Considerations

HDT infrastructures operate across jurisdictions, complicating enforcement. Cross-border data flows and cloud infrastructures require international coordination. Governance efforts should include harmonized regulatory standards, mutual recognition frameworks, cross-border audit cooperation, international ethical guidelines. Without coordination, regulatory arbitrage may undermine protective measures.

From Data Governance to Simulation Governance

The core insight emerging from this analysis is that HDTs require a transition from data governance to simulation governance. Data governance regulates collection and processing. Simulation governance must regulate predictive modeling scope, behavioral intervention mechanisms, cognitive impact, feedback loop dynamics, and institutional power distribution. This shift reflects the transformation of digital systems from passive record-keeping tools into active behavioral infrastructures.

Toward Proactive and Adaptive Governance

Given the evolving nature of HDTs, governance must be adaptive rather than reactive. Key principles include continuous risk reassessment, iterative regulatory review, multi-stakeholder participation, experimental regulatory sandboxes, and transparent public reporting. Regulation should not merely respond to harm but anticipate structural risks inherent in predictive simulation systems. Human Digital Twins challenge foundational assumptions of digital regulation. They blur boundaries between data and identity, prediction and intervention, assistance and control. Existing regulatory instruments—while necessary—are insufficient to address the cognitive, structural, and systemic risks of behavioral simulation. Effective governance must therefore integrate enhanced accountability mechanisms, dynamic consent models, rights-based protections, structural oversight institutions, simulation-focused regulatory paradigms. Only through such comprehensive governance can HDTs fulfill their potential for social benefit without undermining autonomy, equality, and democratic integrity.

Conclusion

Human Digital Twins (HDTs) represent a decisive shift in the evolution of digital technologies—from data collection systems to predictive behavioral infrastructures. Unlike traditional digital profiles, HDTs do not merely document past actions; they simulate possible futures, anticipate decisions, and increasingly participate in shaping the environments within which those decisions unfold. This transformation carries profound ethical implications.

This paper has argued that the normative significance of HDTs lies not primarily in data privacy concerns, but in their capacity to model, predict, and influence human cognition and behavior. By integrating continuous data streams with machine learning architectures, HDTs create asymmetries of predictive knowledge that may undermine cognitive autonomy, entrench structural inequalities, and intensify institutional power. The ethical risks identified—cognitive manipulation, inference opacity, representational authority, discriminatory feedback loops, and attention commodification—extend beyond individual harm and implicate democratic institutions and social justice.

Existing governance frameworks, centered on data protection and risk classification, remain necessary but insufficient. HDTs require a transition from static data governance to dynamic simulation governance. Such an approach must incorporate accountability mechanisms, behavioral impact assessments, contestability rights, and protections for cognitive autonomy. Regulatory models should address not only the fairness of outputs but also the structural conditions under which predictive systems operate, including economic incentives and power concentration.

At the same time, HDTs hold substantial promises. In healthcare, they may enable early diagnosis and personalized treatment; in safety-critical environments, they may prevent harm; in urban systems, they may improve resource allocation. The ethical task is therefore not prohibition but principled design and responsible deployment. Human Digital Twins must be embedded within normative frameworks that prioritize human dignity over optimization imperatives and democratic oversight over opaque automation.

Ultimately, the question raised by HDTs is not merely how accurately we can simulate human behavior, but how far societies should permit predictive systems to shape it. As behavioral simulation technologies become increasingly sophisticated, safeguarding cognitive freedom and institutional accountability will be central to preserving human agency in digitally mediated environments. Proactive, interdisciplinary governance is therefore essential—not only to mitigate harm, but to ensure that the digital doubles we create remain instruments of human flourishing rather than mechanisms of subtle domination.

References:

1. A-Nuwaiser, W. (2025) Ethical and emotional design challenges in human-digital twin interaction: a systematic review. Journal of Intelligent System and Applied Data Science (JISADS), vol. 3, Issue 1, pp. 1-17. https://jisads.com/index.php/1/article/view/34
2. Braun, M. (2022) Ethics of digital twins: four challenges. J Med Ethics, vol. 48, no. 9, pp. 579–580. https://pubmed.ncbi.nlm.nih.gov/34380743/
3. Favela, L. H., & Amon, M. J. (2023). The ethics of human digital twins: Counterfeit people, personhood, and the right to privacy. IEEE 3rd International Conference on Digital Twins and Parallel Intelligence (DTPI). Orlando, FL: IEEE. https://ieeexplore.ieee.org/document/10365409
4. Gaffinet, B., Al Haj Ali, J., Naudet, Y., Panetto,H. (2025) Human digital twins: A systematic literature review and concept disambiguation for industry 5.0. Computers in Industry, Vol. 166. https://doi.org/10.1016/j.compind.2024.104230
5. Helbing, D. & Argota Sánchez-Vaquerizo, J. (2023) Digital Twins: Potentials, Ethical Issues, and Limitations. Handbook on the Politics and Governance of Big Data and Artificial Intelligence, chapter 3, pages 64-104, Edward Elgar Publishing. https://arxiv.org/pdf/2208.04289
6. NDTP Ethics Strategy (2025) https://www.ndtp.co.uk/wp-content/uploads/2025/07/NDTP-Ethics-Strategy.pdf

BISTATIC ISAR IMAGING BASED ON 802.11BE SIGNAL

Assoc. Prof. Dr. Todor Kostadinov
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Abstract: *The scope of this work is focused on the implementation of 802.11be waveform imaging technique with Bi-static Inverse Synthetic Aperture Radar (BISAR) concept. The topology of BISAR consists of stationary transmitter and receiver and a moving target, the geometry is described by kinematic vector equations. The mathematical model of WiFi 7 signal used to illuminate the complex object is described. Image reconstruction technique in direction of range is carried out by correlating the signal reflected by the object with an emitted waveform. The azimuth direction compression is implemented by a Fourier transform. The imaging model is verified by a numerical experiment.*

Keywords: *Wireless local area connection, 802.11be, Bi-static ISAR*

1. INTRODUCTION

The application of remote imaging techniques for perimeter security and observation purposes [1] is gaining popularity. The contemporary proximity broadband data communication technologies provide excellent coverage, signal to noise ratio and satisfactory resolution. The bi-static radar topology of BISAR technology with spatially distributed transmitter and receiver correspond to the aforementioned communication systems to apply the principle of synthetic aperture radar for image extraction. One of the most popular technologies for data communication is the wireless area network - Wifi, especially in urban areas where the number of transmitters is vast. [2] addresses an overview of the WiFi signal. An application of 802.11be in radar systems is presented in [3]. The wireless signal propagation, range resolution and characteristics is discussed in [4].

An overview the imaging properties of the 802.11be signal in terms of passive remote sensing is presented, as the spatial signals radiated by third-part transmitters are exploited to illuminate a target of opportunity [5, 6]. The use of higher frequency and broader band in the latest wireless standards along with the advanced modulation techniques suggest good basis for radar imaging. Description of the WiFi signal range resolution properties as well as signal to noise ratio are performed. Signal formation

approaches and processing methods are also subjects of investigation in order to prove the concept of remote sensing by wireless systems for early warning and security systems application. This paper aims to present the problem of formation and analytical description of WiFi signal in a BISAR topology, derive the mathematical model of 802.11be signal of an arbitrary transmitter, signal formation and reconstruction procedure.

2. GEOMETRY OF BISAR

The BISAR topology comprised of a wireless LAN stationary transmitter and receiver both located on a premise buildings is presented in Fig. 1. As a target consider an unmanned aerial vehicle (UAV). The BISAR geometry components – 802.11 transmitter, target and receiver are located in a Cartesian coordinate system *Oxyz*. The target of observation presented as an array of scattering points is presented in an independent coordinate system *OXYZ*. $\mathbf{R}^s$ and $\mathbf{R}^r$ represent the position vectors of the transmitter and receiver respectively in a coordinate system Oxyz.

The position vector of *ijk*th point scatterer denoted as $\mathbf{R}_{ijk}$ is situated in the coordinate system *OXYZ*, $\mathbf{R}_{00}(p)$ represents the target position vector of the mass center at the moment *p*. From the geometry in Fig. 1 the following kinematical vector equations for the distance from the transmitter to an arbitrary point scatterer of the target and also the distance from the same scattering point to the receiver:

$$\mathbf{R}^s{}_{ijk}(p) = \mathbf{R}^s(p) + \mathbf{AR}_{ijk} = \mathbf{R}^s - \mathbf{R}_{00}(0) - \mathbf{V}\left(\frac{N}{2} - p\right)T_p + \mathbf{AR}_{ijk} \quad (1)$$

$$\mathbf{R}^r{}_{ijk}(p) = \mathbf{R}^r(p) - \mathbf{AR}_{ijk} = \mathbf{R}^r - \mathbf{R}_{00}(0) - \mathbf{V}\left(\frac{N}{2} - p\right)T_p - \mathbf{AR}_{ijk} \quad (2)$$

The round trip range distance transmitter- *ijk*th scattering point of target-receiver is defined as:

$$R_{ijk}(p) = \left|\mathbf{R}^s{}_{ijk}(p)\right| + \left|\mathbf{R}^r{}_{ijk}(p)\right|. \quad (3)$$

The kinematic vector equations 1-3 define the BISAR signal model with a geometry presented in fig. 1

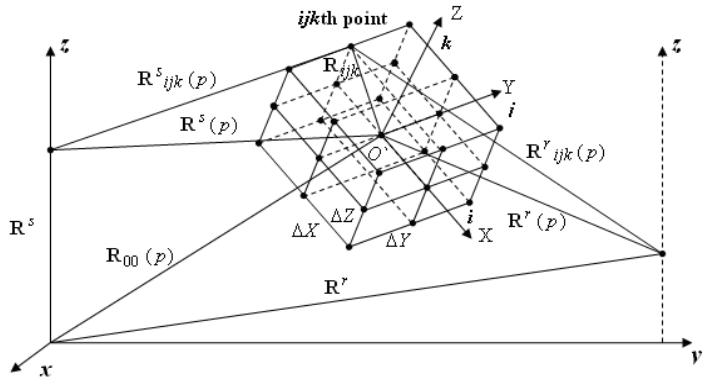


Figure 1. Geometry of 802. 11 be scenario

3. COMMUNICATION WITH THE GRID, V2G PROTOCOL

Signal waveform

The waveform of 802.11be signal is comprised of an OFDM (Orthogonal Frequency Division Multiplexing) structure with total bandwidth up to 320 MHz according to the number of subcarriers 4096 respectively for the largest bandwidth and multi resource units (RU) allocation per single user. When the subcarrier spacing is changed, the cyclic prefix duration per symbol also changes. The wireless LAN model waveform can be expressed by an IFFT equation, i.e.

$$S(t) = \sum_{k=-\lfloor N_{ST}/2 \rfloor}^{\lceil N_{ST}/2 \rceil - 1} a_k \ exp[j2\pi k\Delta f(t - N_{ST}T_S \ )] \quad (4)$$

Where

a_k is the value of the resource element (*k*,) and subcarrier configuration (complex QAM symbol assigned to the *k*th subcarrier), *k* is the frequency domain index,

$exp[j2\pi k\Delta ft]$ is the exponential term that represents the *k*th subcarrier with spacing Δf,

N_{ST} is the total number of active subcarriers (up to 4096 for 320 MHz bandwidth),

Δf is the subcarrier spacing of 78.125 kHz increasing the symbol length in 802.11be

T_S is the cyclic prefix (guard interval) duration.

BISAR signal model

The discrete form of the BISAR signal model represents a delayed copy of the 802.11be waveform, expressed as:

$$S(k,p) = \sum_{i,j,k} \sum_{k=-\lfloor N_{ST}/2 \rfloor}^{\lceil N_{ST}/2 \rceil} a_k \; exp[\, j2\pi k \Delta f (t - N_{ST}.T_s - t_{ijk}(p))] \quad (5)$$

where the time delay of the signal reflected by *ijk*-th scattering point is denoted as $t_{ijk}(p) = \dfrac{R^s_{ijk}(p) + R^r_{ijk}(p)}{c}$.

BISAR signal image reconstruction

The image reconstruction consists of two operations – range and azimuth compression. The range compression is a cross correlation procedure between the signal received by the receiver signal and the waveform emitted by the transmitter, i.e.

$$I(\hat{k}, p) = \sum_{k} S(k, p).S_l^{q\mu}(k - \hat{k}) \quad , \quad (6)$$

where $\hat{k}$ is the range coordinate of the scattering point in the BISAR image.

The azimuth compression or the complex image extraction is performed by fast Fourier transform, i.e.

$$I(\hat{k}, \hat{p}) = \frac{1}{N} \sum_{p} I(\hat{k}, \hat{p}) \exp\left(- j \frac{2\pi.p.\hat{p}}{N} \right) \quad , \quad (7)$$

where $\hat{p}$ is the azimuth coordinate of the *p*th scattering point in the BISAR image, N is the total amount of azimuth samples.

4. BALANCING TECHNIQUES

To verify the proposed signal model, BISAR geometry and image reconstruction algorithm, a numerical experiment is carried out. The target is moving rectilinearly in a Cartesian 3-D coordinate system of observation $Oxyz$. The transmitter is situated on the following coordinates : $x^s = -75$ m; $y^s = -25$ m; $z^s = 25$ m. Coordinates of the receiver: $x^r = 75$ m; $y^r 25$ m; $z^r = 12$ m. target parameters are: module of the vector velocity

$V = 10$m/s; $\alpha = \pi/4$; $\beta = \pi/4$; $\gamma = \pi/2$. The coordinates of the mass-center: $x_{00}(0) = 25$ m; $y_{00}(0) = 25$ m; $z_{00}(0) = 20$ m.

Target is depicted in a 3-D grid with the following dimensions of the cells $\Delta X = \Delta Y = \Delta Z = 0.5$ m.

BISAR Scenario

It is assumed that the target is moving rectilinearly in a 3-D Cartesian coordinate system of observation $Oxyz$. Target parameters: module of the vector velocity $V = 10$ m/s, Velocity guiding angles: $\alpha = \pi/4$, $\beta = \pi/4$, $\gamma = \pi/2$. The coordinates of the targets mass-center: $x_{00}(0) = 25$ m; $y_{00}(0) = 50$ m; $z_{00}(0) = 50$ m. Coordinates of the 5GNR transmitter: $x_S = -250$ m; $y_S = 510$ m, $z_S = 150$ m. Coordinates of the 5GNR receiver: $x_R = 300$ m; $y_R = -510$ m, $z_R = 52$ m.

The target geometry, a UAV - helicopter, is depicted in a 3-D regular grid with cell's dimensions $\Delta X = \Delta Y = \Delta Z = 0.5$ m (Fig. 2).

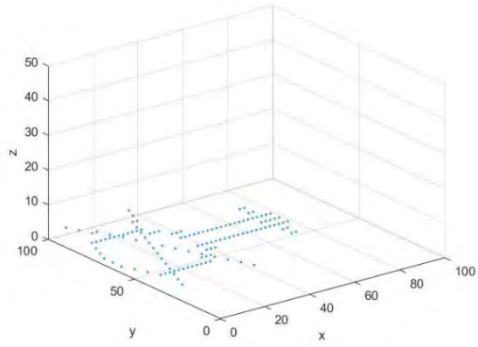


Fig. 1 Target geometry (UAV - helicopter)

B. Experimental results and Discussion

Based on the expression (6), a signal matrix $S(k,p)$ is calculated. The real component of $S(k,p)$ complex matrix is depicted in Fig. 3.

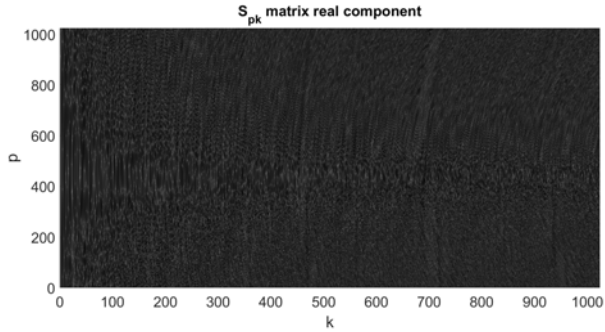


Fig 2. A real component of S(k, p) signal matrix

The imaginary component of $S(k,p)$ complex matrix is depicted in Fig. 3.

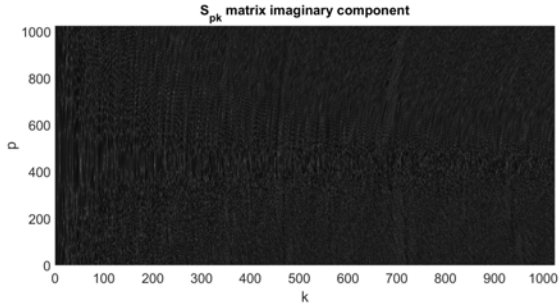


Fig. 3 An imaginary component of S(k, p) signal matrix

The real component of range compressed $S(k,p)$ complex matrix is depicted in Fig. 5.

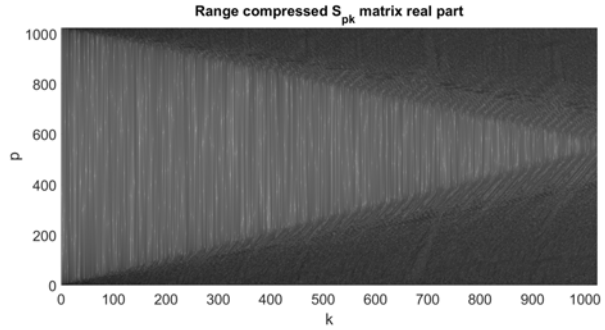


Fig. 4 The real component of range compressed S(k, p) matrix

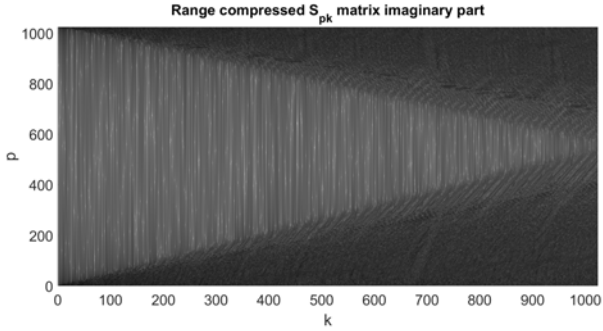


Fig. 5 The imaginary component of range compressed S(k, p) matrix

The imaginary component of range compressed complex signal $S(k,p)$ is depicted in Fig. 6. The real component of the azimuth compressed complex signal $S(k,p)$ after range compression is depicted in Fig. 7.

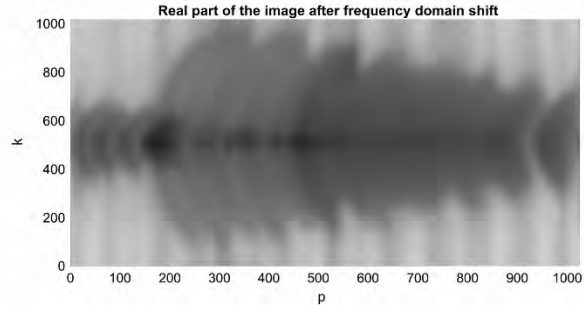


Fig. 6 The real component of azimuth compressed complex signal S(k, p) after range compression

The imaginary component of azimuth compressed complex signal $S(k,p)$ after range compression is depicted in Fig. 8. The amplitude value of the final image is presented in Fig. 9. Having in mind that the range resolution is 10 m., the quality of the obtained BISAR image is satisfactory. The separate scattering points are not resolved but the target silhouette is seen.

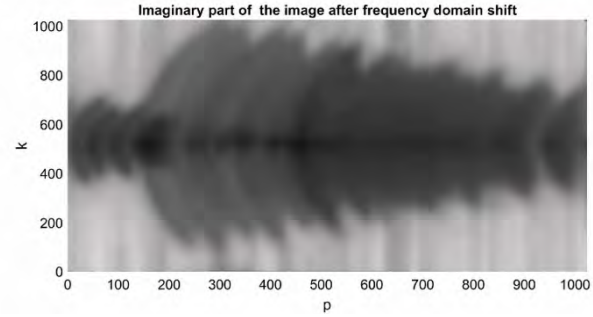


Fig. 7 The imaginary component of azimuth compressed S(k, p) complex signal after range compression

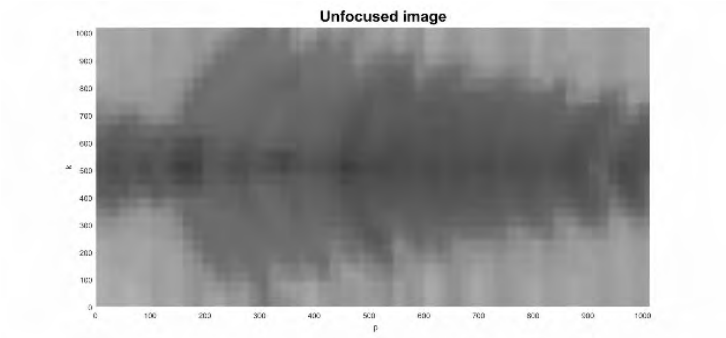


Fig. 8 The final reconstructed BISAR image

CONCLUSION

This paper investigated the geometry, signal modeling, and target imaging framework of a bistatic inverse synthetic aperture radar (Bi-ISAR) system employing IEEE 802.11be signals as illuminators of opportunity. A deterministic signal model for the bistatic configuration was derived, and the target imaging process was formulated in terms of direct and inverse spatial transformations. The image formation chain, including phase error correction, range compression via cross-correlation, and azimuth compression through Fourier transformation, was established. Simulation results verified the validity of the proposed signal model and demonstrated the capability of IEEE 802.11be waveforms to provide effective target imaging performance in Bi-ISAR applications.

ACKNOWLDEGMENT

In memory of prof. Andon Lazarov

References:

1. 38.211 NR; Physical channels and modulation (Release 15). https://www.sharetechnote.com/html/5G/5G_Waveform.html
2. E. Dahlman, S. Parkvall, and J. Skold, “Overview of 5G NR: The next generation wireless access technology,” Academic Press 2020, 5 61-63.
3. B. Liu, X. Lyu, and W. Fan, “Analysis of 5G Signal for Radar Application,” October 2022, Journal of Physics Conference Series 2356(1):012027, DOI: 10.1088/1742-6596/2356/1/012027.
4. B. R. Sri, “Executive summary of the thesis synthetic aperture radar imaging using 5G NR Signals, advisors: Stefano Tebaldini, Marco Manzoni, academic year 2022/23, Politecnico, Milano 1863. https://www.politesi.polimi.it/handle/10589/215084.

5. B. Tan, E. S. Lohan et al., “Improved sensing and positioning via 5G and mm wave radar for airport surveillance, https://www.sesarju.eu/sites/default/files/documents/sid/2021/papers/SIDs_2021_paper_4.pdf
6. P. Samczyński, K. Abratkiewicz, M. Płotka, et al. 5G network-based passive radar, IEEE Transactions on Geoscience and Remote Sensing, 2022 60 1-9.

IMAGE RECONSTRUCTION OF 802.11 WAVEFORM BISAR SIGNAL BASED ON L0 NORM MINIMIZATION

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Abstract: *a l0 norm minimization in signal sparse decomposition of a wireless LAN signal in two dimensions of a BISAR imaging case is discussed. BISAR geometry and kinematical equations with stationary transmitter and receiver, and a moving target are analytically described. The BISAR signal model is based on 802.11be waveform. The signal formation is derived as a redundant Fourier basis sparse decomposition. Image reconstruction procedure addresses minimization of l0 norm in the received complex signal. The minimization of resulting non-zero point scatterers is presented.*

Keywords: *Sparse decomposition, L0 minimization image reconstruction, Compressed sensing*

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is an advanced remote sensing technology widely employed for high-resolution observation and monitoring of the Earth's surface. The imaging process is based on the transmission of electromagnetic pulses and the coherent reception of the backscattered echoes from the observed scene [1–3]. The resulting SAR image is represented in a two-dimensional coordinate system comprising the slant-range coordinate, associated with the signal propagation delay, and the azimuth (cross-range) coordinate. High range resolution is achieved through the use of wideband transmitted waveforms, whereas high azimuth resolution is obtained by coherently integrating the reflected signals over the synthetic aperture interval.

Conventional SAR image formation algorithms are predominantly based on matched-filter processing and correlation techniques. Their achievable resolution is fundamentally constrained by the bandwidth of the transmitted signal and the effective synthetic aperture length, as dictated by the Nyquist sampling criterion. To overcome these limitations, particularly in scenarios where the observed scene exhibits sparse structure,

Compressed Sensing (CS) has emerged as a powerful alternative framework. CS exploits the sparsity of the target reflectivity distribution and formulates the image reconstruction problem as the minimization of an objective function consisting of a data-fidelity term and a sparsity-promoting regularization term, typically based on the (l0)-norm [4].

Significant research efforts have been devoted to (l0)-norm optimization methods for sparse image reconstruction, including Basis Pursuit Denoising (BPDN), wavelet-based deconvolution, and compressed sensing approaches, as well as sparse feature selection techniques such as the Least Absolute Shrinkage and Selection Operator (LASSO). These problems are commonly formulated as (l_1)-regularized least-squares optimization programs, which can be transformed into convex quadratic optimization problems and efficiently solved using numerical techniques such as interior-point algorithms [5, 6]. Sparse image reconstruction based on (l0)-norm minimization has demonstrated the capability to recover high-dimensional sparse vectors from a limited set of linear measurements whose dimensionality is substantially lower than that of the unknown signal [7, 8].

The application of compressed sensing to SAR imaging has been extensively investigated in the literature. In [9], a wideband synthetic aperture imaging system was developed to reconstruct sparse scenes from a reduced number of non-adaptive linear measurements by exploiting the sparsity of point-like scatterers and solving a convex (l0)-norm optimization problem. Compressed sensing approaches for three-dimensional imaging of buried point targets using continuous-wave ground-penetrating radar were presented in [10, 11]. These studies demonstrated that sparse target distributions can be accurately reconstructed from a significantly reduced number of frequency samples and antenna positions, thereby decreasing data acquisition time and computational complexity. Furthermore, an (l0)-norm-based compressive noise radar imaging algorithm was proposed in [12], incorporating sparsity constraints within a convex optimization framework.

In contrast to most existing compressed sensing formulations, where both the sparse image and the received signal are represented as one-dimensional vectors, the present work adopts a two-dimensional matrix representation for both the SAR image and the SAR signal. Such a formulation preserves the inherent spatial structure of the image formation process and enables the development of a mathematically rigorous sparse reconstruction framework directly in the two-dimensional signal domain.

The primary objective of this study is to develop a SAR image reconstruction algorithm based on sparse decomposition of the two-dimensional

SAR signal and sparsity-constrained optimization. Starting from the geometrical model of the observed surface and the mathematical model of SAR signal formation, a two-dimensional sparse image reconstruction framework is derived. The proposed approach integrates sparse signal decomposition with norm-minimization techniques to improve image resolution and target localization. The remainder of the paper is organized as follows. Section 2 presents the SAR geometry and kinematic model. Section 3 derives the mathematical model of the SAR signal. Section 4 introduces the sparse decomposition framework for image reconstruction. Section 5 develops the proposed sparse imaging algorithm based on norm-minimization optimization. Section 6 presents numerical simulation results and performance analysis, while Section 7 summarizes the main conclusions of the study.

2. BSAR KINEMATICAL EQUATION AND TOPOLOGY

Fig. 1 presents BSAR scenario. Wireless transmitter, receiver located on the land surface and a target are all situated in Cartesian coordinate system *Oxyz*, where $\mathbf{R}^{s}(p)$ is the current position vector of the WiFi transmitter in discrete time instant *p*, $\mathbf{R}_{00'}(p)$ is the current position vector of the mass center of the target, $\mathbf{R}^{r}$ is the stationary position vector of the receiver. The target presented as an assembly of point scatterers is depicted in Cartesian coordinate system *OXYZ*, where $\mathbf{R}_{ijk}$ is the position vector of the *ijk*th point scatterer – fig. 1.

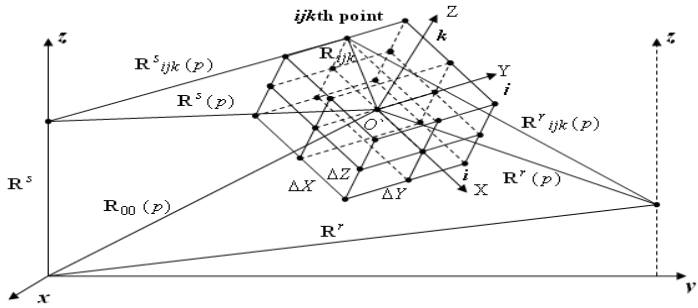


Figure 1. Geometry of a BSAR scenario

The position vector of the target's mass center with respect to the satellite transmitter, $\mathbf{R}^{s}_{0'}(p)$ is defined by

$$\mathbf{R}^{s}_{0'}(p) = \mathbf{R}^{s}(p) - \mathbf{R}_{00'}(p) \quad (1)$$

where $\boldsymbol{R}^{s}(p) = \boldsymbol{R}^{s}(0) - \boldsymbol{V}\left(\frac{N}{2} - p\right)T_p$ is the position vector of the satellite, $\mathbf{R}_{00'}(0) = \mathbf{R}_{00'}(0) - \mathbf{V}\left(\frac{N}{2} - p\right)T_p$ is the position vector of the mass centre of target; $\mathbf{V}$ is the target's velocity vector, $p = \overline{1,N}$ is the current number of the satellite transmitter's *P* phase code segment, *N* is the full number of emitted segments used for purposes of the aperture synthesis, T_p - time acquisition interval, (pT_p) - the discrete slow time.

The position vector of the target's mass center with respect to the receiver, $\mathbf{R}^{r}_{0'}(p)$ is defined by

$$\mathbf{R}^{r}_{0'}(p) = \mathbf{R}^{r} - \mathbf{R}_{00'}(p) = \mathbf{R}^{r} - R_{00'} - \mathbf{V}\left(\frac{N}{2} - p\right)T_p. \quad (2)$$

The position vector of the *ijk*th point scatterer with respect to the transmitter, $\mathbf{R}^{s}{}_{ijk}(p)$ is defined by

$$\mathbf{R}^{s}{}_{ijk}(p) = \mathbf{R}^{s}_{0'}(p) + \mathbf{A}\mathbf{R}_{ijk} =$$

$$\mathbf{R}^{s}_{0'}(p) - \mathbf{R}_{00'}(0) - \mathbf{V}\left(\frac{N}{2} - p\right)T_p + \mathbf{A}\mathbf{R}_{ijk}. \quad (3)$$

where **A** is the coordinate transition matrix.

The elements of the transformation matrix $\mathbf{A}$ are determined by the Euler expressions

$$a_{11} = \cos\psi\cos\varphi - \sin\psi\cos\theta\sin\varphi;$$
$$a_{12} = -\cos\psi\sin\varphi - \sin\psi\cos\theta\cos\varphi;$$
$$a_{13} = \sin\psi\sin\theta;$$
$$a_{21} = \sin\psi\cos\varphi + \cos\psi\cos\theta\sin\varphi;\ a_{31} = \sin\theta\sin\varphi;$$
$$a_{22} = -\sin\psi\sin\varphi + \cos\psi\cos\theta\cos\varphi; a_{32} = \sin\theta\cos\varphi;$$
$$a_{23} = -\cos\psi\sin\theta;\ a_{33} = \cos\theta. \quad (4)$$

The projection angles ψ,θ and φ, defining the space orientation of the 3-D grid are calculated by components A,B,C of the normal vector to the plane that specifies the position of the target, and coordinates of the vector velocity, i.e.

$$\psi = \arctan\left(-\frac{A}{B}\right); \quad \theta = \arccos\frac{C}{[(A)^2+(B)^2+(C)^2]^{\frac{1}{2}}} \quad (5)$$

$$\varphi = \arccos\frac{V_x B - V_y A}{\{[(A)^2+(B)^2][(V_x)^2+(V_y)^2+(V_z)^2]\}^{\frac{1}{2}}}. \quad (6)$$

The components A,B,C of the normal vector are determined by the components of the target's mass centre position vector $\mathbf{R}_{00'}(0) = [x_{00'}(0), y_{00'}(0), z_{00'}(0),]^T$, vector velocity of the target and vector position of an arbitrary reference point $\mathbf{R}_0 = [x_0(0), y_0(0), z_0(0)]^T$ in the co-ordinate system $Oxyz$ by expressions

$$\begin{aligned} A &= V_z[y_{00'}(0) - y_0(0)] - V_y[z_{00'}(0) - z_0(0)]; \\ B &= V_x[z_{00'}(0) - z_0(0)] - V_z[x_{00'}(0) - x_0(0)]; \\ C &= V_y[x_{00'}(0) - x_0(0)] - V_x[y_{00'}(0) - y_0(0)]. \end{aligned} \quad (7)$$

The position vector of the *ijk*th point scatterer with respect to the receiver, $\mathbf{R}^s{}_{ijk}(p)$ is defined by

$$\mathbf{R}^r{}_{ijk}(p) = \mathbf{R}^r_{0'}(p) - \mathbf{A}\mathbf{R}_{ijk} = \mathbf{R}^r - \mathbf{R}_{00'}(0) - \left(\frac{N}{2} - p\right)T_p - \mathbf{A}\mathbf{R}_{ijk}. \quad (8)$$

The round trip distance transmitter-target-receiver is defined by

$$R_{ijk}(p) = \left|\mathbf{R}^s{}_{ijk}(p)\right| + \left|\mathbf{R}^r{}_{ijk}(p)\right|. \quad (9)$$

Equation (9) is used in calculation of the raund trip time delay of the signal reflected by a particular generic point scatterer from the target area while signal modeling.

3. BISAR SIGNAL MODEL AND WAVEFORM

3.1 Signal waveform

The waveform of 802.11be signal is comprised of an OFDM (Orthogonal Frequency Division Multiplexing) structure with total bandwidth up to 320 MHz according to the number of subcarriers 4096 respectively for the largest bandwidth and multi resource units (RU) allocation per single user. When the subcarrier spacing is changed, the cyclic prefix duration

per symbol also changes. The wireless LAN model waveform can be expressed by an IFFT equation, i.e.

$$S(t) = \sum_{k=-\lfloor N_{ST}/2 \rfloor}^{\lceil N_{ST}/2 \rceil - 1} a_k \; exp[j2\pi k\Delta f(t - N_{ST}T_S \;)] \quad (10)$$

Where

a_k is the value of the resource element (*k*,) and subcarrier configuration (complex QAM symbol assigned to the *k*th subcarrier), *k* is the frequency domain index,

$exp[j2\pi k\Delta ft]$ is the exponential term that represents the *k*th subcarrier with spacing Δf,

N_{ST} is the total number of active subcarriers (up to 4096 for 320 MHz bandwidth),

Δf is the subcarrier spacing of 78.125 kHz increasing the symbol length in 802.11be

T_S is the cyclic prefix (guard interval) duration.

3.2 BISAR signal model

The discrete form of the BISAR signal model represents a delayed copy of the 802.11be waveform, expressed as:

$$S(k,p) = \sum_{i,j,k} \sum_{k=-\lfloor N_{ST}/2 \rfloor}^{\lceil N_{ST}/2 \rceil} a_k \; exp[j2\pi k\Delta f(t - N_{ST}.T_s - t_{ijk}(p))] \quad (11)$$

where the time delay of the signal reflected by *ijk*-th scattering point is denoted as $t_{ijk}(p) = \dfrac{R^s_{ijk}(p) + R^r_{ijk}(p)}{c}$.

3.3 BISAR signal image reconstruction

The image reconstruction consists of two operations – range and azimuth compression. The range compression is a cross correlation procedure between the signal received by the receiver signal and the waveform emitted by the transmitter, i.e.

$$I(\hat{k}, p) = \sum_k S(k,p).S_l^{q\mu}(k - \hat{k}) \quad , \qquad (12)$$

where $\hat{k}$ is the range coordinate of the scattering point in the BISAR image.

The azimuth compression or the complex image extraction is performed by fast Fourier transform, i.e.

$$I(\hat{k},\hat{p}) = \frac{1}{N}\sum_{p} I(\hat{k},\hat{p}) \exp\left(-j\frac{2\pi.p.\hat{p}}{N}\right), \qquad (13)$$

where $\hat{p}$ is the azimuth coordinate of the *p*th scattering point in the BISAR image, N is the total amount of azimuth samples.

SAR IMAGE RECONSTRUCTION PROCEDURE

The phase demodulated BSAR signal form is expressed in [15] can be written as follows

$$S(k,p) = \sum_{i,j,k}\sum_{k=-\lfloor N_{ST}/2\rfloor}^{\lceil N_{ST}/2\rceil} a_k \; exp[j2\pi k\Delta f(t - N_{ST}.T_s - t_{ijk}(p))] \qquad (14)$$

The 2-D projection of the 3-D image function on the range and azimuth direction $a_{ijk}(\hat{p},\hat{k})$ can be extracted from (14) by inverse space transform form from 2-D signal plane into 2-D image space, i.e.

Tailor expansion of $\omega[t_{ijk\min}(p) - t_{ijk}^{\hat{k}}(p)]$ yields

$$\omega[t_{ijk\min}(p) - t_{ijk}^{\hat{k}}(p)] = \frac{2\pi}{N}\hat{p}.p + \Phi(p),$$

where

$$\Phi(p) = a_2(pT_p)^2 + ... + a_m(pT_p)^m \qquad (15)$$

denotes the phase term of higher order, $\hat{p}$ is the azimuth coordinate of *ijk*th scatterer. Then the equation (15) can be rewritten as

$$a_{ijk}(\hat{p},\hat{k}) = \sum_{p=\overline{1,N}}\left\{\sum_{k=\hat{k}}^{\hat{k}+K-1}\left[\hat{S}(p,k).\mathbf{exp}(j\Phi(p)\right] \mathbf{exp}[j\pi b((k-\hat{k}+1)\Delta T)]\right\} \times \mathbf{exp}\left\{j\left[\frac{2\pi}{N}\hat{p}p\right]\right\}. \qquad (16)$$

Based on (18) the following 2-D complex image extraction algorithm can be defined.

1. Phase correction of higher order (motion compensation) by the expression

$$\tilde{S}(p,k) = \hat{S}(p,k).\mathbf{exp}(j\Phi(p)). \qquad (17)$$

The values of the polynomial coefficients of $\Phi(p)$ are unknown and can be defined by application of different optimization procedures combined with appropriate image cost function.

2. Range compression by cross-correlation

$$\widetilde{S}(\hat{p},\hat{k}) = \sum_{k=\hat{k}}^{\hat{k}+K-1} \widetilde{S}(p,k)\mathbf{exp}[j\pi b((k-\hat{k}+1)\Delta T)] \quad , \quad (18)$$

where $\hat{k}$ is the discrete coordinate of *ijk*th point scatterer on the range direction.

3. Azimuth compression (complex image extraction) by inverse Fourier transformation

$$a_{ijk}(\hat{p},\hat{k}) = \sum_{p=\overline{1,N}} \widetilde{S}(p,\hat{k})\mathbf{exp}\left\{ j\left[\frac{2\pi}{N}\hat{p}p \right] \right\}. \quad (19)$$

Phase Correction Based on l0 Minimization

L0 norm minimization is applied on the sparse BISAR model by performing operations on the waveform.

A Sparse Decomposition is performed over the sparse signal

$S(t) = \sum_{i=1}^{N} x_i \varphi_i + n$

This is a redundant Fourier dictionary decomposition because the OFDM waveform itself is generated from Fourier basis functions.

In order to perform Exact L0 norm optimization the following condition must be met for ideal sparse reconstruction to be achieved:

min $\|x\|_0$ is subject to $\|y - \Phi x\|^2_2 \leq \varepsilon$

where:

$\|\boldsymbol{x}\|_0 = \#\{i : x_i \neq 0\}$

x_0 is used to minimize number of scattering centers and preserve agreement with measured BISAR signal. The product is minimal number of physical scatterers generating the measured waveform.

Regularized Form Image Reconstruction with L0 Regularization

$J(x) = \|y - \Phi x\|^2_2 + \lambda\|x\|_0$

It is performed in two steps according to the terms in the latter equation – provide fidelity of the waveform and exclude excessive scatterers

Provide e*ntropy-L0 Hybrid Model*

$H = -\Sigma\ p_i\ \ln(p_i),\quad p_i = |x_i|^2 / \Sigma|x_j|^2$

$J(x,a) = \|y - \Phi(a)x\|^2_2 + \lambda\|x\|_0 + \mu H(x)$

This step estimates autofocus parameters, minimizes image entropy and number of scatterers.

Recovery Condition

$K < 0.5\ (1 + 1/\mu(\Phi))$

is the dictionary coherence. Due to 802.11be OFDM waveform number of subcarriers is 4096 and the bandwidth is expands to 320 MHz, the resulting sensing matrix tends to have relatively low coherence, which improves sparse recovery performance.

***A** BISAR Reconstruction*

$\hat{x} = \arg\min [\ ||y - \Phi(a)x||^2_2 + \lambda||x||_0 + \mu H(x)\ ]$

Let $\Phi_s(p)$ be the phase correction function, defined at the *s*-th stage.

Then the phase correction of higher order is accomplished by multiplication of the demodulated BSAR signal, matrix $\hat{S}(p,k)$ with the exponential term $\exp(j\Phi_s(p)$, i.e.

$$\widetilde{S}_s(p,k) = \hat{S}(p,k)\exp(j\Phi_s(p)). \quad (20)$$

After current phase correction (20) a complex image extraction that includes cross correlation (19) and Fourier transformation (20) is performed.

Define the power normalized image as

$$\hat{a}_{ijk_s}(\hat{p},\hat{k}) = \frac{\left|a_{ijk_s}(\hat{p},\hat{k})\right|^2}{\sum_{p=0}^{N-1}\sum_{k=0}^{K-1}\left|a_{ijk_s}(\hat{p},\hat{k})\right|^2}. \quad (21)$$

where $a_{ijk_s}(\hat{p},\hat{k})$ is the complex image after *s*th stage.

Define the image cost function as an entropy function of the normalized BSAR image

$$H_s = -\sum_{p=0}^{N-1}\sum_{k=0}^{K-1}\hat{a}_{ijk_s}(\hat{p},\hat{k})\ln[\hat{a}_{ijk_s}(\hat{p},\hat{k})]. \quad (22)$$

The procedure is applied until the global minimum value of the entropy H_s is acquired. The estimation of the phase correction coefficient ceases for the argument that minimizes the entropy image cost function

$$\hat{a}_m = \arg\min_{\Phi}\left\{H[\hat{a}_{ijk_s}(\hat{p},\hat{k})]\right\} \quad (23)$$

4. NUMERICAL EXPERIMENT

To verify the geometry of BSAR scenario with 802.11be waveform, a numerical experiment has been carried out. To prove the correctness of the developed reconstruction procedure of the digital image it is assumed that the target, an unmanned aerial vehicle, moving rectilinearly in a three dimensional Cartesian coordinate system of observation $Oxyz$.

Coordinates of the WiFi transmitter at the moment $p = N/2$ are: $x^s = -25\text{m}, y^s = 50\text{m}$; $z^s = 5\text{m}$. target velocity: $v_x^s = 1.4\text{m/s}$, $v_y^s = 1.4\text{m/s}$. Coordinates of the stationary receiver: $x^r = 30\text{m}$, $y^r = 50\text{m}$ and $z^r = 5\text{m}$. The trajectory parameters of the target: velocity $V = 2$ m/s; guiding angles $\alpha = \pi/4$, $\beta = \pi/4$, $\gamma = \pi/2$; coordinates of the target's mass-centre at the moment $p = N/2$: $x_{00} - 25\text{m}$, $y_{00} = 15\text{m}$, $z_{00} = 5\text{m}$. Wifi waveform parameters: frequency $f = 6.10^9$ Hz, number of subcarriers in the segment $K = 4096$, range sample number 1024, Wifi segments number during aperture synthesis $N = 1024$, time acquisition interval $T_p = 3.10^{-2}\text{s}$. The geometry of the helicopter is depicted in a 3-D coordinate grid with cell's dimensions $\Delta X = \Delta Y = \Delta Z = 1\text{m}$ (Fig.1).

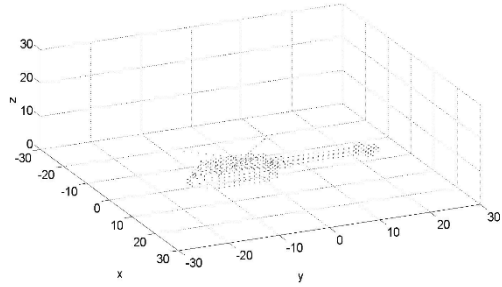


Figure 2. Target image of a helicopter in 3-D coordinate system

Numerical results of BSAR signal modeling, and stages of signal processing and image reconstruction are illustrated in Figs. 2÷8. Based on (15) a real and imaginary part of a BSAR signal calculated and presented in Fig. 3 and 4.

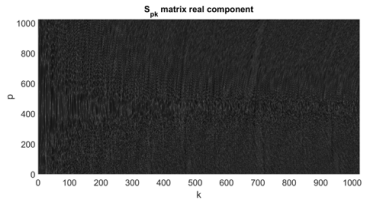


Figure 3. BSAR signal (real part)

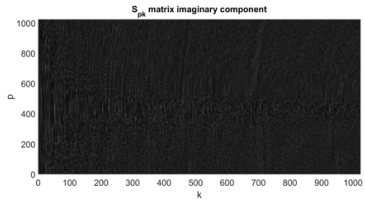


Figure 4. BSAR signal (imaginary part)

A real and imaginary part of a range compressed BSAR signal is calculated by (10) and depicted in Fig. 5 and 6.

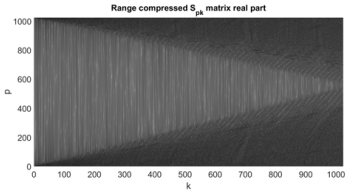


Figure 5. Range compressed BSAR signal (real part)

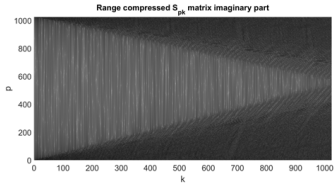


Figure 6.Range compressed BSAR signal (imaginary part)

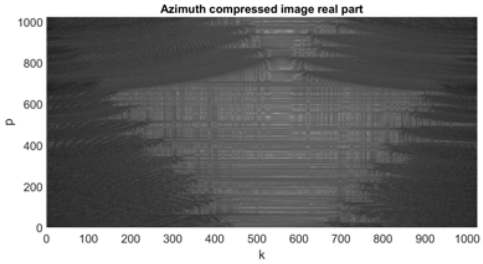


Figure 7. Azimuth compressed BSAR signal (real part)

A real and imaginary part of an azimuth compressed BSAR signal is calculated by (21) and after frequency shifting are depicted in Fig. 7 and 8.

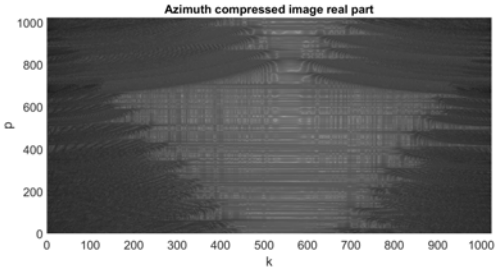


Figure 8. Azimuth compressed BSAR signal (imaginary part)

In Fig. 9 the image of a helicopter is depicted after BSAR signal modeling and image reconstruction after cross correlation range compression and Fourier transform azimuth compression is depicted. The imaging quality is poor due to lack of azimuth resolution in the waveform.

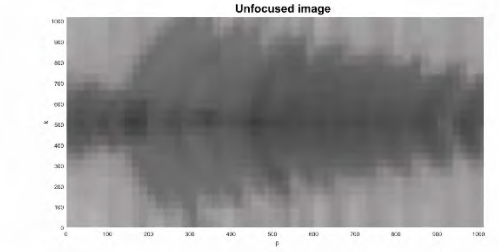


Figure 9. BSAR image of the helicopter

In Fig. 10 the BSAR image of a helicopter is depicted after all stages of the image reconstruction procedure that includes higher order phase correction.

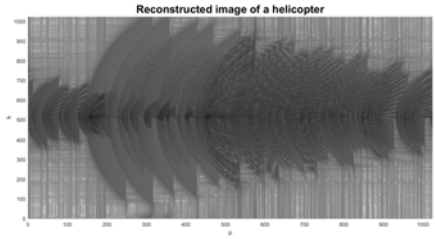


Figure 10. BSAR image of the helicopter after autofocus procedure

The quality of the image is more satisfactory as can be noticed, with less blurring image. The results of the numerical experiment illustrate the resolution capabilities of WiFi BSAR system with uncooperative transmitter.

CONCLUSION

In this work, the geometry of bistatic synthetic aperture radar (BSAR) employing 802.11 be transmitters of opportunity and a dedicated receiver has been investigated, together with the corresponding signal formation and target imaging processes. A deterministic BSAR signal model waveforms has been derived, demonstrating that signal formation and image reconstruction can be interpreted as direct and inverse spatial transformations. The complete image reconstruction procedure, including phase correction, cross-correlation-based range compression, and azimuth compression through Fourier transformation, has been formulated and analyzed.

Furthermore, a nonconventional image reconstruction approach based on compressed sensing and two-dimensional l0-norm minimization has been developed. A discrete model of the observed surface and the mathematical framework for BSAR/SAR signal formation have been established, while sparse image representation in the Fourier domain has been

employed to improve reconstruction performance. Unlike conventional one-dimensional l0-norm minimization techniques applied to image vectors, the proposed method utilizes a two-dimensional formulation directly on the image matrix, providing a more natural representation of the imaging problem.

Numerical experiments have been conducted to validate both the signal modeling framework and the proposed image reconstruction algorithm. The obtained results confirm the effectiveness and correctness of the developed methods, demonstrating successful target imaging using WiFi 7 waveforms. Moreover, the analytical and experimental findings indicate that the performance of the compressed sensing-based reconstruction algorithm strongly depends on the sparsity of the observed scene, with surfaces containing a limited number of dominant scatterers yielding superior image resolution and reconstruction quality.

ACKNOWLDEGMENT

In memory of prof. Andon Lazarov

References:

1. Liu J., Zhu J., Yan F., Zhang Z. Compressive Sampling and ℓ1 Minimization for SAR Imaging with Low Sampling Rate. Inverse Problems and Imaging, 2013.
2. Li G., Xin D., Li W., Yang L., Wang D., Zhou Y. Approximate Observation Weighted ℓ2/3 SAR Imaging under Compressed Sensing. Sensors, 2024.
3. Chen W., Geng J., Meng F., Zhang L. Sub-Nyquist SAR Imaging and Error Correction via an Optimization-Based Algorithm. Sensors, 2024.
4. Liu M., Pan J., Zhu J., Chen Z., Zhang B., Wu Y. A Sparse SAR Imaging Method for Low-Oversampled Staggered Mode via Compound Regularization. Remote Sensing, 2024.
5. Ma Q., Jiao R., Han Y., Huang H., Lai T., Shen P., Wang Q. HomoR-CS: A Homogeneous Region-Based Compressed Sensing Method for SAR Tomography. International Journal of Applied Earth Observation and Geoinformation, 2024.
6. Chen W., Geng J., Meng F., Zhang L. Pseudo-L0-Norm Fast Iterative Shrinkage Algorithm Network: Agile Synthetic Aperture Radar Imaging via Deep Unfolding Network. Remote Sensing, 2024.
7. Paramasivam S., Kaliyaperumal V. Reconstruction of Synthetic Aperture Radar Data Using Hybrid Compressive Sensing and Deep Neural Network Algorithm. International Journal of Communication Systems, 2024.

8. Zhao Y., Xiao D., Pan Z., Ling B., Tian Y., Zhang Z. Sparse SAR Imaging Based on Non-Local Asymmetric Pixel-Shuffle Blind Spot Network. Remote Sensing, 2024.
9. Zhang H., Ni J., Li K., Luo Y., Zhang Q. Nonsparse SAR Scene Imaging Network Based on Sparse Representation and Approximate Observations. Remote Sensing, 2023.
10. Gao S., Wang W., Wang M., Zhang Z., Yang Z., Qiu X., Zhang B., Wu Y. A Robust Super-Resolution Gridless Imaging Framework for UAV-Borne SAR Tomography. 2024.
11. Ren Y., Zhan X., Hu Y., Ma X., Liu L., Wang M., Shi J., Wei S., Zeng T., Zhang X. Towards Spatial Feature Regularization in Deep-Learning-Based Array-SAR Reconstruction. 2024.

SIMULATIONS AND RESEARCH OF BEARING GEARS

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Burgas Free University

Abstract: *The effective use of digital simulations can help product development teams significantly reduce their current costs and the risks associated with introducing new products. Commonly referred to as CAE (Computer-Aided Engineering), digital simulations enable engineers to explore and evaluate a wider range of design alternatives, reducing the direct costs associated with expensive physical prototypes and allowing faster, better-informed design decisions. NX Motion Simulation provides a comprehensive set of tools for analysing velocities, accelerations, torques, trajectories, and other motion-related parameters, using the MSC.Adams and FunctionBay RecurDyn solvers.*

Keywords: *Digital simulations; Design decisions; NCS Motion Simulation; Velocity and acceleration analysis*

Each rolling bearing consists of an inner ring (ring), an outer ring (ring), rolling elements (grains or rollers) and a separator. With the help of the separator, an even distribution of the rolling elements is achieved.

The rolling bearing can be considered as a planetary mechanism, in which the inner and outer rings, the separator and the rolling elements are, respectively, central wheels a and b, the guide h and the satellite g.

If the balls or rollers of the bearing are connected to some part, the axis of rotation of which coincides with the axis of the bearing, when the bearing rotates, the part carried by the balls or rollers will rotate i1 times slower than the inner ring and i3 times slower than the outer ring, with one of the two rings stationary. In this case, the bearing becomes a transmission mechanism - a bearing reducer with a gear ratio of i1 or i3.

When the two bearing rings rotate simultaneously in different directions, the gear ratio can theoretically be as large as desired.

By fixing one of the bearing units /separator, inner ring or outer ring/, schemes for realizing different gear ratios can be obtained. It is also important which unit is leading or driven.

In the design of a friction mechanical transmission with a single component /rolling bearing/, the kinematic scheme closely resembles a scheme of a planetary gear mechanism with two or more degrees of freedom.

The effective use of digital simulations can help development teams reduce many of their ongoing costs and the resulting risk of introducing new products. Commonly known as CAE (Computer Aided Engineering), digital simulations allow for the consideration and evaluation of more design options, which reduces the direct costs associated with expensive physical prototypes and allows for faster and better-founded design decisions. NX Motion Simulation includes a full suite of tools for analyzing velocities, accelerations, torques, trajectories, and more, using the MSC.Adams and Function Bay RecurDyn solvers.

Simulation of a friction mechanical transmission with two components inside each other

Simulation 1

This simulation defines the process of torque transmission from the main shaft 1 to the output shaft 2, which is attached to the cage of a 30202 bearing. The torque transmission is carried out thanks to the interaction, through friction forces, between the rollers and the inner ring of the bearing. These forces cause the rollers to rotate around their own axis, since the outer ring is fixedly attached, a satellite movement of the rollers and the cage around the inner ring also occurs.

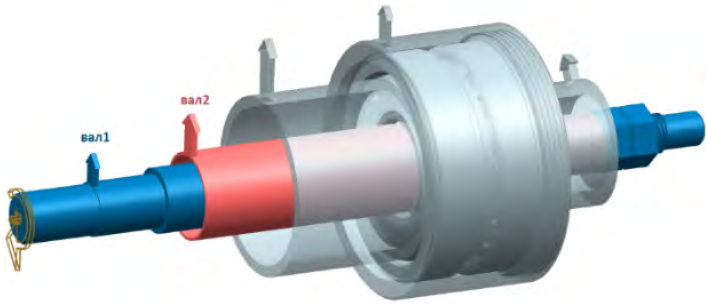


Fig. 1. Simulation 1- designation of the output and input shafts

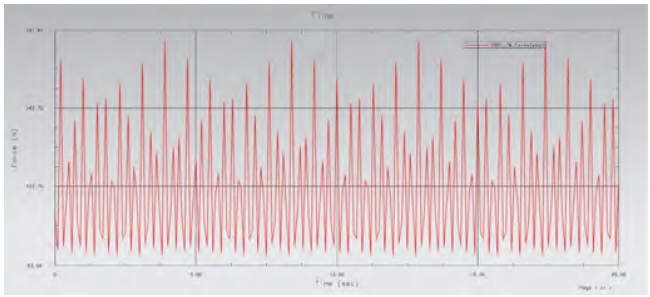


Fig. 2. Dependency analysis – simulation 1

Simulation 2

Here is defined the process of transmitting torque from input shaft 3, located between bearings 30202 and 30208 to output shaft 4, which is attached to the separator of bearing 30208. A characteristic feature is the fact that if output shaft 2 is not fixed, then torque will be transmitted to it as a result of the interaction between the outer ring, which is fixedly attached together with input shaft 3, and the rollers of bearing 30202. This option is shown in the simulation.

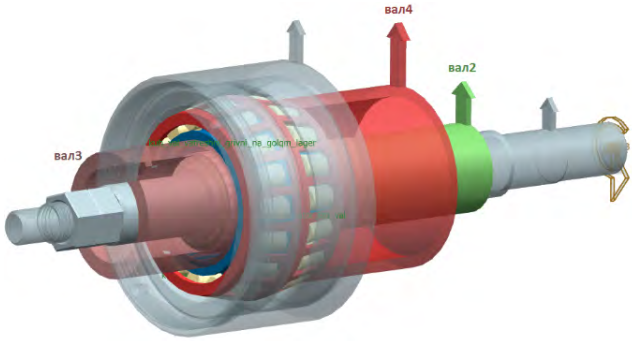


Fig. 3. Simulation 2 - designation of the output and input shafts.

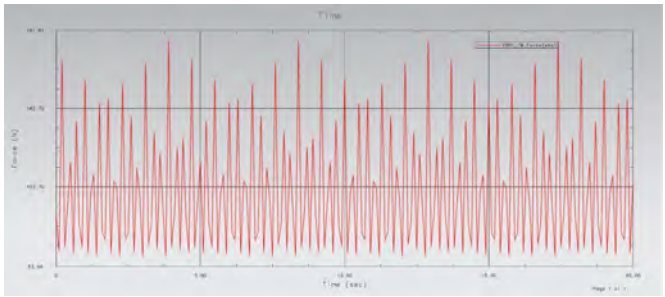


Fig. 4. Dependency analysis – simulation 2

Simulation 3

This simulation defines the process of transmitting torque from the main shaft 1 to the shafts: shaft 3 and shaft 4, with shaft 2 fixed. When the separator of bearing 30202 is fixed, the rotational movement from the rollers is transmitted not to the separator, but to the outer ring of the same bearing, respectively to the inner ring of bearing 30208, i.e. there is a variant of simulation 2, but the input shaft is the main shaft 1. Of course, the direction of rotation of shafts 3 and 4 is opposite to the initial direction of rotation.

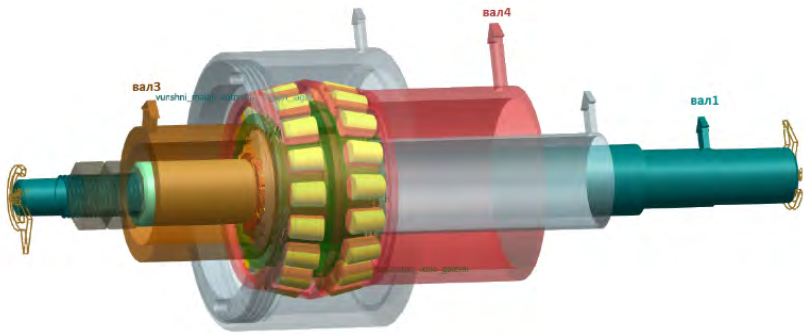


Fig. 5. Simulation 3 - designation of the output and input shafts

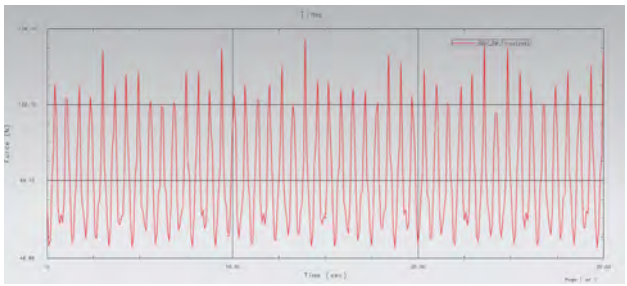


Fig. 6. Dependency analysis – simulation 3

Simulation 4

Shaft 2 is again fixed, but the torque is transmitted through the mechanism housing. The torque transmission is similar to Simulation 3, with the difference that the sequence is from bearing 30208 to main shaft 1.

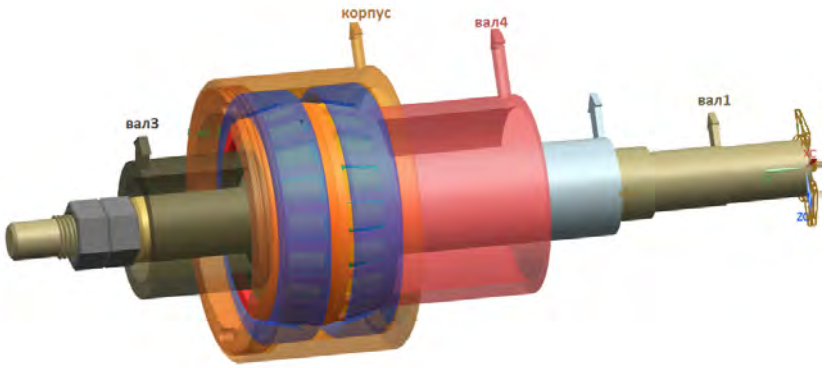


Fig.7. Simulation 4 - designation of the output and input shaft

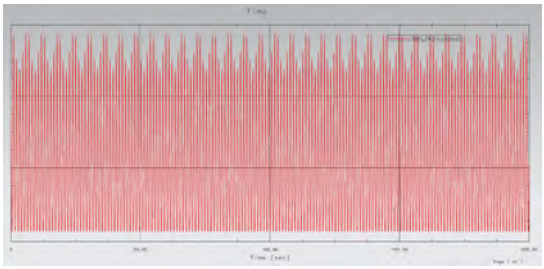


Fig.8. Dependency analysis – simulation 4

Simulation of a friction mechanical transmission with two components one after the other

Simulation 1

In this simulation, the process of torque transmission from the main shaft 1 to the output shaft 2 and shaft 3, which are attached to the bearing cages 30202 and 30208, is defined. The torque transmission is carried out thanks to the interaction, through friction forces, between the rollers and the inner rings of the bearings. These forces cause the rollers to rotate around their own axis, since the outer ring is fixedly attached, a satellite movement of the rollers and the cage around the inner ring also occurs.

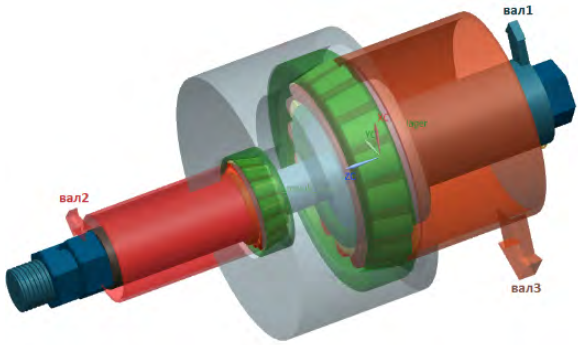


Fig. 9. Simulation 1 - designation of the output and input shafts

Simulation 2

The simulation defines the process of torque transmission from the main shaft 1 to the output shaft 2 and the housing, with a fixed shaft 3. A reversal of motion is realized at shaft 4 due to the locking of shaft 3.

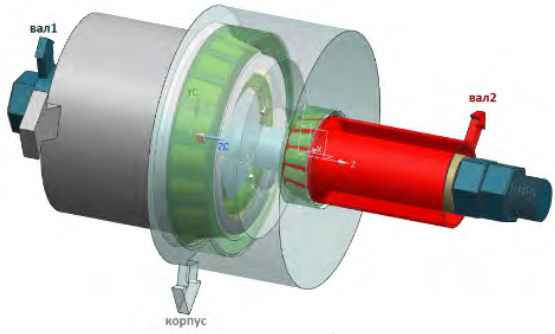


Fig. 10. Simulation 2 - designation of the output and input shafts

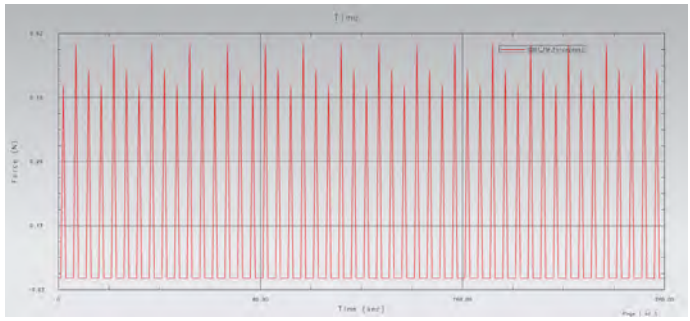


Fig. 11. Dependency analysis – simulation 2

CONCLUSION

• The analogy with planetary and differential gear mechanisms makes it possible to segment the resulting mechanisms and make an exemplary classification of the friction gear.

• It will help to accurately analyze, quickly calculate and correctly apply the used design (scheme) of the friction gear.

• It will help to correctly and economically design friction gears.

• With the help of computer modeling, the right decisions can be made quickly and accurately, the necessary experiments can be carried out to derive the technically and design-effective design.

• Modeling in NX is based on the revolutionary Siemens Synchronous Technology, providing a unique approach to 3D design to accelerate the work of the designer compared to traditional techniques currently used.

References:

1. Litvin F.L., Theory of gearing, M., Nauka, 1968.
2. Minchev, N., Zhivkov, V., Enchev, K., Stoyanov, P. Theory of mechanisms and machines. S., Technology, 1991.
3. Nedev, Ts., Galabov, V., Lilov, A., Andonov, A. Mechanical Science, S., 2002.
4. Braren R., Planetengetriebe,
5. Patentschrift, #631247, Schweiz und Liechtenstein, F16H 1/28, 1978.
6. Jelaska D., Gears and geardrives, John Wiley, 2012.
7. Moaveni S., Engineering fundamentals, Minnesota State University, 2005.

ALGORITHMIC SUSTAINABILITY OR DIGITAL GREENWASHING? A CRITICAL ANALYSIS OF GREEN AI WITHIN ESG AND CORPORATE SOCIAL RESPONSIBILITY FRAMEWORKS

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Abstract: *Artificial intelligence is increasingly being presented as a strategic tool for sustainable development, resource optimization, ESG management and climate solutions. However, recent international analyses show that AI is not just an "intangible" digital technology, but a system dependent on large-scale physical infrastructure – data centers, power grids, cooling systems, land, water, high-performance chips and critical minerals. The 2026 UNU-INWEH report emphasizes that the environmental cost of AI should be assessed not only through carbon emissions, but also through the water and land footprint, as well as the impact on local communities. This raises the question of whether some of the public claims about "green" AI do not conceal real environmental externalities. The purpose of this text is to analyze the ecological footprint of artificial intelligence, its relationship with ESG performance, the risk of digital greenwashing and the social consequences related to water resources and environmental justice.*

Keywords: *Artificial intelligence; Environmental footprint; ESG performance; Digital greenwashing; Environmental justice*

Introduction

The last decades of the 20th century were characterized by some of the most remarkable industrial and technological achievements. At the same time, we have also witnessed some very serious environmental revelations. The latter were made possible by the work of Erin Brockovich, who openly spoke about cases of contamination with hexavalent chromium (Chromium-6 or Cr(VI)). The substance is highly toxic and carcinogenic and gained popularity during the lawsuits against Pacific Gas and Electric Company in Hinckley (a city in the state of California) in the 1990s. The outcome of the case was the imposition of a historic compensation of $ 333

million. The case is a symbol of corporate environmental irresponsibility, and yet in recent years new evidence has emerged that the problem is far from being overcome.

In 2025–2026, a number of studies and journalistic investigations established the presence of dangerous concentrations of Chromium-6 in various regions of the world. Particularly worrying is the case in Indonesia, where documents uncovered by international investigative organizations show that a major nickel mining company had data on contamination of drinking water sources with concentrations reaching almost three times the legal limit, without the information being publicly disclosed. The case is particularly significant because it is linked to nickel supply chains for electric vehicles and the “green” energy transformation, which calls into question how sustainable the transition is in fact sustainable. In 2025–2026, Erin Brockovich draws public attention to a new environmental issue: the rapid expansion of the AI industry and, in particular, the construction of large data centers. Her position is not directed against artificial intelligence as a technology, but against the lack of transparency about the real environmental costs - water, energy, land, carbon emissions and e-waste. (Brockovich,2026). Her main argument is that the "digital" economy has a strong material dimension. In April 2026, she announced a map to track AI data centers and their impact on local communities, insisting on permitting regimes, strict limits on water use, buffer zones and environmental assessments. (Brockovich, E.,2025).

1. The Rise of Green AI

The concept of Green AI is increasingly established as a basic concept in the development of artificial intelligence. Thus, an emphasis is placed on reducing the carbon footprint and sustainable use of resources in the development and implementation of AI systems. Since the traditional approach is based on increasing and maximizing the productivity and accuracy of algorithms, it can be said that Green AI is a balanced model, In which the assessment of Technological progress is reflected both in computing and in its impact on the environment. The emergence of the concept is directly related to the exponential growth of computing resources required to train modern generative models, such as large language models (LLMs) and generative AI systems. According to Schwartz, the development of increasingly complex algorithms leads to a significant increase in electricity consumption and computing power. This leads to another question: "the long-term sustainability of the current model of technological development."

The concept of Green AI is gaining particular relevance in the context of global ESG policies. It aims to achieve the United Nations Sustainable Development Goals. More and more technology companies are integrating sustainability into their corporate strategies, declaring the use of renewable energy, optimization of algorithms and the construction of energy-efficient data centers. In this context, Green AI is presented as a tool for reducing carbon emissions, improving resource efficiency and supporting the ecological transition in various economic sectors. Artificial intelligence finds application in the management of energy systems, and smart grids, climate change monitoring, circular economy and optimization of production processes, which creates the conditions for real positive effects on sustainable development.

However, alongside these benefits, contemporary scientific literature increasingly raises the question of whether Green AI represents a truly sustainable technological transformation or whether there is a risk of a new form of digital greenwashing. While companies emphasize the potential of AI to support sustainability, a number of studies show that behind digital services lies a significant physical infrastructure requiring huge amounts of electricity, water and raw materials. The United Nations University report (2026) emphasizes that the ecological footprint of AI should be considered in its entirety, including the consumption of energy, water resources, land and critical minerals. Similar conclusions are contained in the analysis of Zewe (2025), according to which the training and operation of generative AI models can generate significant carbon emissions and put serious pressure on local water resources through the cooling systems of data centers.

As a result, Green AI is becoming the subject of a growing scientific and public debate that goes beyond technological efficiency and encompasses issues related to corporate accountability, ESG management and environmental justice. The question is increasingly being asked whether the sustainability of AI should be measured solely by the benefits that the technology creates, or by the net balance between the value created and the environmental resources required for its functioning. In this sense, Green AI is emerging not only as a technological concept, but also as a new direction in sustainable development research, which requires an integrated approach to innovation, transparency and responsible corporate governance.

2. Ecological footprint of artificial intelligence

2.1. Energy consumption and carbon emissions

It is becoming clear that the development of AI is related to the increased consumption of electricity by data centers. It is indicated (International Energy Agency, 2024) that global consumption reaches 415 TWh. This is approximately 1.5% of global electricity consumption. It is also said that according to the IEA, this consumption could double to about 945 TWh by 2030.

The data is not only the result of AI, but also of the accelerated servers and high-performance computing used to train and run AI models. They increase the data from the statistics. It can be concluded that the carbon footprint of AI is a combination of the consumption in the regions where the data centers are located.

2.2. Water consumption

Another serious footprint is the water footprint, It is not always sufficiently reflected in the reports of AI infrastructure. Water is used in data centers to cool them and indirectly through electricity produced from water-intensive energy sources. The literature (Privette, Barros, and Cai, 2026) states that corporate reporting is often not fully transparent and does not provide comparable information on water consumption in such data centers. This makes processes like planning or regulation, and risk assessment difficult for communities already exposed to water stress.



2.3. Land and resource use

Land is another resource needed for data centres, power infrastructure, and energy facilities. What is more, the production of chips, servers, and hardware depends on critical raw materials and complex global supply chains.

Therefore, the environmental footprint of AI should not be limited to electricity alone. It includes carbon, water, land, mineral extraction, e-waste, and local environmental stresses.

3. Artificial Intelligence and ESG Performance

AI has real potential to support ESG management. Through big data processing, machine learning and text analysis, AI can be used to monitor ESG risks, assess sustainability, analyse reports, track supply chains and detect discrepancies between corporate claims and external data. For example, research on NLP approaches to analysing ESG communication shows that digital tools can compare corporate reports with external sources and media narratives. Thus, AI can be useful not only for creating ESG content, but also for verifying its credibility. In this sense, AI should not be seen as a one-sided environmental problem. It can be a tool for sustainable management, but only if its own infrastructure is subjected to the same standards of transparency, accountability and environmental assessment that are required of other industries.



4. Artificial intelligence and digital greenwashing

Paradoxically, AI simultaneously assists in analysing ESG data, especially when creating convincing but misleading sustainability messages. Such models create texts that sound like ESG reports. At the same time, they do not reflect real improvement in environmental or social indicators.

Another study (Davidescu, Manta, Bîrlan, Miler and Niță. 2026) shows that NLP methods can detect discrepancies between corporate ESG self-description and external public narratives. This is particularly important because greenwashing is no longer just a marketing problem. It is an issue of governance, accountability and trust.

Zhang (2024) also examines the role of AI in curbing greenwashing practices, emphasizing the potential of AI to improve transparency and support sustainable growth. However, there is a risk that technology companies present AI as a climate solution without sufficiently disclosing its own costs – electricity, water, land and emissions. This is what can be defined as "digital greenwashing".

5. AI, water resources and environmental justice

The water issue turns AI infrastructure not only into an environmental but also a social problem. When data centers are located in areas with limited water resources, local communities can bear burdens that are not evenly distributed – pressure on water supplies, higher infrastructure costs, noise, land use and conflict between economic development and environmental security.

Brockovich emphasizes that the problem of water and data centers should not be addressed through individual local cases, but through regional planning between technology companies, local governments, water operators and communities.

In this context, Erin Brockovich's activism in 2026 fits into the broader debate on the transparency of AI infrastructure. She emphasizes the lack of sufficient public information about the construction of data centers and the concerns of local communities. This approach is directly related to ESG logic: sustainability cannot be proven through corporate claims alone, but requires verifiable data, publicity and stakeholder participation.

Conclusion

Artificial intelligence has a dual importance for sustainable development. On the one hand, it can support ESG analysis, risk management,

environmental monitoring and the detection of greenwashing. On the other hand, its own infrastructure creates a significant environmental footprint related to electricity, water, land, emissions and resources. Therefore, Green AI should not be assumed to be automatically sustainable. A more rigorous governance approach based on transparency, infrastructure lifecycle, water and carbon footprint accountability, regional planning and environmental justice is needed. Only under such conditions can AI be a real tool for sustainable development, and not a new form of digital greenwashing.

References:

1. Aczel, M., Chamanara, S., Matin, M., Farsi, A., Marwala, T., & Madani, K. (2026). Environmental cost of AI's energy use: Carbon, water and land footprints. United Nations University Institute for Water, Environment and Health. https://doi.org/10.53328/INR26RMA002 Davidescu, A. A., Manta, E. M., Bîrlan, I., Miler, A.-M., & Niță, S.-C. (2026). Detecting greenwashing in ESG disclosure: An NLP-based analysis of Central and
2. Brockovich, E. (2025). Can AI help solve our water problems? The Brockovich Report., https://www.thebrockovichreport.com
3. Brockovich, E. (2026, April 9). The new pollution is data—and it's hiding in plain sight. The Brockovich Report. ,https://www.thebrockovichreport.com
4. Privette, A.P., et al. (2026). Data Centers Water Footprint: The Need for More Transparency. AGU Advances.
5. Schwartz, R., Dodge, J., Smith, N.A., & Etzioni, O. (2020). Green AI. Communications of the ACM, 63(12), 54–63. https://doi.org/10.1145/3381831
6. United Nations University Institute for Water, Environment and Health. (2026). Artificial intelligence and the future of global water and energy demand. Hamilton, ON: UNU-INWEH.
7. United Nations University Institute for Water, Environment and Health. (2026). The environmental cost of artificial intelligence: Carbon, water and land footprints. Hamilton, Canada: UNU-INWEH.
8. Zewe, A. (2025). Explained: Generative AI's environmental impact. Massachusetts Institute of Technology. MIT News.

DIGITALIZATION OF THE PROPERTY REGISTER IN THE REPUBLIC OF BULGARIA

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Abstract: *This report traces the principal stages of the process of establishing a property register in the Republic of Bulgaria, as well as the principles on which that process rests. The digitalization of the register, as an element of the introduction of electronic governance in the country, is a necessary reform which, beyond improving the services rendered to citizens, must also build upon the requirements for safeguarding the recorded instruments and the persons who derive rights from them.*

Keywords: *electronic governance, cadastre, property register, immovable property, digitalization, security of transactions, publicity*

The digitalization of the property register is an element of the introduction of electronic governance in the Republic of Bulgaria, the purpose of which is to enhance the efficiency and quality of the services provided to citizens by the executive, legislative and judicial authorities. Regrettably, the process is unfolding amid a series of obstacles and delays. The establishment of a property register and its digitalization are topical questions also on account of their significance for legal certainty in transactions in immovable property, which have grown considerably in recent years. Traditionally kept on paper, property registers are likewise subject to inevitable transformation in the age of digitalization. Their digitalized "doubles" will facilitate inquiries into the legal status of immovable property, but they could equally be exposed to the risks characteristic of the global information environment. Thus, instead of guaranteeing legal certainty, digital registers could hinder it.

The principal aim of this report is to cast a critical eye on digitalization in this sphere of social relations in our country and to underscore the importance of well-balanced legal regulation that simultaneously ensures observance of the fundamental principles of the system for recording the instruments concerning the legal status of immovable property, alongside the inevitable digitalization of social relations in this field.

The property register is an essential element of the system for recording statutorily prescribed legal instruments that pertain to immovable property within the territory of the Republic of Bulgaria. It is important to note the exclusive jurisdiction of national legislation in this sphere of legal regulation, irrespective of the nationality of the holders of the rights *in rem* over the properties. The principle that the applicable law is that of the country in whose territory the property is situated (*lex rei sitae*) is universal to private international law.

The recording of the legal instruments and circumstances designated by law constitutes non-contentious (*ex parte*) proceedings, governed by the Civil Procedure Code (CPC) of the Republic of Bulgaria, the Property Act, the Recording Regulation, the Cadastre and Property Register Act, the Notaries and Notarial Activity Act and the Regulation for its application. Recordings constitute *procedural acts of the recording judge and of the recording office, consisting in the entry and arrangement, within the books maintained, of the instruments provided for by law, so as to give them publicity* (Article 1 of the Recording Regulation).

This activity is carried out by the recording judges and by the officials of the Registry Agency and is of considerable legal significance. Its principal purpose is to bring certainty to transactions in immovable property by giving publicity to their legal status, that is, by making the corresponding information accessible. The rules governing the procedure are mandatory in character and may not be altered at the will of the parties to civil-law relations, namely the interested persons and the holders of rights.

In our country, recording was first regulated in 1910. During the socialist period, until 1996, it was performed by notaries, who were salaried by the State and incorporated into the structure of the district courts. In 1996, when the private notariat was established in the Republic of Bulgaria, notarial activity in respect of transactions was separated from recording activity. The latter was assigned to recording judges and to recording offices established at the district courts throughout the country. Notwithstanding this distinction, recordings continue to be regulated as a type of notarial act under Article 569, item 5 of the CPC.

The property register is a comparatively new phenomenon for our legal system. A fundamental precondition for its creation is the establishment of a cadastre encompassing the complete cadastral survey of all immovable property within the territory of the Republic of Bulgaria, namely: land plots, buildings and self-contained units within buildings. These constitute the so-called cadastral units. The creation of both a cadastre and a property register is a lengthy and arduous process, preceded by cadastral surveying

and by furnishing each item of immovable property with a unique identification number, known as an identifier. A permanent bilateral link, based on this identifier, operates between the cadastre and the property register.

The establishment of a property register in our country is regulated by the Cadastre and Property Register Act (hereinafter "the CPRA"), which entered into force on 1 January 2001. The overall assessment of this normative act is positive, for through it the legal foundation was laid for refining the rules of recording by means of a fundamental change to the system itself: from a *personal* system it is to transition to a *real* one. The real system is considerably more precise and complete than the personal one and secures the conditions for faster and more accurate inquiries regarding each property.

The personal system was adopted in our country from France and Italy at the beginning of the twentieth century. Under this system, the files of the individual properties are kept under the names of the transferors. For this reason, it is at times difficult to ascertain who the current holder of the right is. The system has shortcomings which, given the contemporary dynamics of transactions in immovable property, would create great uncertainty in civil commerce. The incomplete information recorded under this system is one such shortcoming. Thus, for example, it is not possible to record acquisition by prescription by a third party, since in such acquisition there is no transferor. A further shortcoming is the multitude of books (the incoming register, the register for inquiries, the alphabetical index and others) in which the recording must be effected and, correspondingly, in which the sought information must be verified. This inevitably renders the verification of the current status of properties slow and unreliable.

The property register, which is associated with the real system (also known as the property-based system of recording), consists of the files of the individual items of immovable property. Each item of immovable property has an independent file, kept under an identifier. There shall be recorded in the register the instruments by which the right of ownership is recognized or transferred, or by which another right *in rem* over immovable property is created, transferred, modified or terminated; the injunctions and mortgages over the properties; as well as other acts, circumstances and juridical facts for which recording is provided for by law (Article 3 of the CPRA). The property register is also defined as a system of data on the immovable property within the territory of the Republic of Bulgaria, for its individualization, and on the owners, the holders of other rights *in rem*, mortgages, injunctions and other rights provided for by law (Article 2 of

Ordinance No. 2 of 2005 on the maintenance and preservation of the property register).

The property files in their classic, paper-based form are created for properties that have an identifier (Article 65, paragraph 1 of the CPRA). The rule applies equally to their electronic files (Article 65, paragraph 4 of the same Act). In addition, the law provides for files to be opened for all properties that existed prior to the introduction of the cadastre and with which transactions are effected (Article 71, paragraph 2 of the CPRA). The aim is that, in this manner, the register should genuinely encompass all immovable property within the territory of the country.

Elucidating the essence and the principles underlying the creation and maintenance of the recording system as a whole, and of the property register in particular, is the requisite foundation upon which the specific rules for its digitalization ought to be developed. The very concept of digitalization in the context under consideration is identical to the universal meaning of the word.

The property register is public. Its aim is to give publicity to legal instruments, juridical facts and circumstances exhaustively established by law, thereby guaranteeing legal certainty in transactions in immovable property. On the other hand, however, the instruments subject to recording are public and accessible to interested persons, which means that any interested party may make inquiries and obtain the information required, as well as copies of or extracts from the property files. What has been said applies to an even greater extent to digital registers. For this reason, it will be of particular importance how access to the electronic data is to be regulated for the “interested” persons, their counsel, the respective competent authorities and third parties.

Digitalization and the creation of the property register are complex and protracted processes, entrusted to the Registry Agency and, more specifically, to its 113 subdivisions throughout the country, namely the recording offices. This activity is an important element of the introduction of electronic governance in the country, prior to which citizens and businesses still submit property certificates to the Registry Agency on paper. The aim of the process is for State officials to bear the obligation, and to possess the technical means, to verify the recordings, notations and deletions in the property files entirely *ex officio*, as the executive authority in the Republic of Bulgaria has repeatedly pledged since the adoption of the Cadastre and Property Register Act in 2000.

As of 2017, however, interested persons must still deliver by hand, to the individual subdivisions of the Agency, 12 principal certifying

documents. In respect of 8 of these, numerous preceding legislative amendments are required: to 49 statutes and 70 subordinate normative acts. The most intractable is considered to be the problem of the certificate concerning the recordings, deletions or notations in the file of a natural or legal person in the property register.

As of the beginning of 2021, the government announced the creation of an "entirely new property register," a step necessitated by the fact that the recording of instruments is still performed under the personal system, a full 20 years after the entry into force of the new act creating the preconditions for property-based recording. A property register has still not been created. In the same year, a public consultation with citizens and institutions was initiated, with the aim of clarifying the causes hampering the process.

It is necessary to clarify that the transition from a personal system of recording to property-based recording presupposes the development of an entirely new property register, the creation of which, under the legislation in force, proceeds through two phases. The first phase begins with the opening of proceedings for the creation of a property register for the respective judicial district by order of the Minister of Justice, which is promulgated in the State Gazette (Article 70 of the CPRA)[1]. Once files have been created for all properties in the respective judicial district, the Minister of Justice issues an order declaring the introduction of the register for that district (Article 73 of the CPRA). This, however, is possible only after the cadastral map and the cadastral registers of the district have been approved and have entered into force. Thus, a precondition for carrying out the activities for the creation of the property register is the completion of the activities connected with the production of a cadastre.

The cadastre is likewise a comparatively new legal phenomenon for our country. According to the legal definition in Article 2 of the CPRA, the cadastre is the aggregate of basic data on the location, boundaries and dimensions of the immovable property within the territory of the country, collected, presented and maintained in an up-to-date state and preserved in accordance with the procedure established by law. The cadastre is created by a separate State structure, the Cadastre Agency. As a rule, the property files are created after the properties have been entered in the cadastre and assigned an identifier, that is, the unique identification number. Ordinance

[1]*The first orders for the opening of proceedings were issued as early as 2006. As of the beginning of 2021, proceedings for the creation of the register had been opened only in Balchik, Blagoevgrad, Kavarna, Dobrich, Asenovgrad, Troyan and Nesebar. Detailed rules were established by Ordinance No. 2 of 21 April 2005.*

No. 2, however, provides for the possibility of preliminary files for properties that do not have an identifier.

In keeping with the rules set out above, the processes are carried out in each judicial district at their own pace, which depends on both objective and subjective factors. Responsibility for the successful conduct of the process rests with the regional cadastre offices and the regional recording offices. At the end of 2022, the National Assembly of the Republic of Bulgaria adopted, on second reading, amendments to the Cadastre and Property Register Act providing for the full digitalization of the property register. This process is to be completed by 30 June 2026. The bill amending and supplementing the Act was proposed by the Ministry of Justice and constitutes a commitment under the Recovery and Resilience Plan (RRP). Pursuant to the newly adopted amendments, the full digitalization of the property register kept by the Registry Agency is envisaged. More specifically, this entails the creation of a common electronic database containing the electronic files of every item of immovable property that has an identifier, together with electronic file dossiers comprising the recorded instruments and the source documents annexed thereto. In this process, complete identity must, first and foremost, be guaranteed between the content of the property's paper file and that of the file in electronic form, as well as of the file dossier. The legal instruments and evidentiary documents annexed to the paper file are to be scanned and added to the respective dossier for the property in electronic form.

A very important precondition for the proper digitalization of the property register is the statutory regulation of the powers of the recording offices in connection with the entry of information into the electronic files of the properties and into the electronic file dossiers of the recorded instruments, together with the documents annexed thereto. This is an essential stage in the reform of the property register and in the transition from a personal to a real system of recording, laid down as early as 2000 with the drafting of the Cadastre and Property Register Act. The digital property register has not been regulated in law as an alternative to the paper register. The two types of databases must continue to exist in parallel, for only in this manner can the preservation and safekeeping of the information of great legal significance contained in them be guaranteed. The leading legal significance of the paper property register must be preserved, and in the event of a discrepancy between the two records, legal effect shall be produced by the record kept on paper, as Article 68 of the CPRA provides.

ANALYSIS OF FIRE HAZARD AND OPERATIONAL-TACTICAL ACTIONS IN EXTINGUISHING FIRES IN ROLLING STOCK THAT OCCURRED IN RAILWAY TUNNELS

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Abstract: *The purpose of the report is to analyze the features of extinguishing fires in rolling stock that occurred in railway tunnels, as well as to propose effective measures to increase safety and improve operational-tactical actions in such incidents. and concluding part. The results achieved, the analyses performed and the proposed measures to increase safety in railway tunnels are summarized. Recommendations for future actions aimed at reducing the risk of fires and increasing the efficiency of emergency teams are included.*

Keywords: *Railway tunnel fires, Rolling stock, Firefighting operations, Emergency response safety*

Rail transport occupies a central and irreplaceable place in modern national and trans-European transport networks. As one of the pillars of the modern economy, it is characterized by extremely high energy efficiency, environmental sustainability and the ability to transport passengers and large volumes of freight over long distances. In the context of global climate change and the pursuit of carbon neutrality, the European Union and the Republic of Bulgaria recognize the railway sector as a priority for development in the coming decades. Large-scale investments in modernization of routes and renewal of rolling stock aim to make railways the most attractive and green alternative to road and air transport.

Despite these undeniable technological and environmental advantages, the operation of the railway system hides specific and high-risk challenges. The high concentration of people and freight in a limited space, combined with the enormous kinetic energy of moving train sets, creates the prerequisites for serious accidents. Factors such as technical malfunctions in outdated rolling stock, depreciation of infrastructure elements, human errors of dispatching and locomotive personnel, as well as unpredictable external

influences (natural disasters or malicious actions), can at any time lead to emergency situations with unpredictable consequences.

Among all possible types of railway accidents, fires in rolling stock are among the most dangerous and destructive events. They develop at an extremely high speed due to the presence of flammable materials in the interior of the carriages, the abundance of high-voltage electrical cables and the specific aerodynamic currents that arise when the train moves. A fire in railway transport directly and immediately puts the lives and health of hundreds of passengers at risk at the same time, causes enormous financial damage to carriers and infrastructure operators and leads to complete paralysis of transport arteries for long periods of time.

The situation becomes critical and extreme when such a fire occurs in a railway tunnel. Tunnels, as specific linear underground facilities, drastically change the dynamics of any incident and turn standard firefighting into a complex and high-risk engineering-tactical operation. In the conditions of a closed underground space, the laws of physics operate differently:

- The lack of natural ventilation leads to a rapid accumulation of toxic gases and thick smoke, which spread along the length of the tunnel tube and deprive people of oxygen in a matter of minutes.
- The chimney effect and thermal load concentrate a huge amount of heat that cannot be dissipated into the atmosphere, with temperatures in the hearth quickly exceeding 1000°C, threatening the structural integrity of the tunnel itself.
- The limited overall space makes the classic evacuation of passengers extremely difficult and panic-inducing, as people often have to move in complete darkness and smoke along narrow service paths or directly on the track.
- The difficult access for rescue teams of the Fire Safety and Civil Protection (FSCP) hinders the rapid deployment of forces and resources, the delivery of extinguishing agents over long distances and the maintenance of reliable radio communication in an underground environment.

The statistics on railway accidents in Bulgaria over the past two decades show a worrying trend - the share of fires in our country is disproportionately high compared to the average European levels. This fact is a direct consequence of the critical obsolescence of the locomotive fleet, the compromised electrical installations in places and the insufficient modernization of the protective systems in the existing tunnel network. Tragic incidents from the recent past, such as the fire on the Sofia - Kardam train,

remain as a painful reminder that safety does not tolerate compromises and requires continuous analysis and prevention.

The relevance of this topic is also determined by the large-scale construction of new, high-speed railway routes in Bulgaria along the European transport corridors. The construction of modern, several-kilometer-long tunnels on the Sofia – Plovdiv and Sofia – Kulata routes requires a fundamentally new approach to fire safety already at the design stage. It is necessary to implement innovative automatic extinguishing systems, forced ventilation, smoke extraction and modern evacuation galleries, combined with perfectly coordinated action plans between railway operators and rescue services.

The main objective of this report is to conduct a thorough and systematic analysis of fire hazards in railway transport, with a focus on the specific risks of incidents in tunnels. By studying international experience, Bulgarian statistics and the current regulatory framework, the following objectives are achieved:

- To identify the main risk factors and sources of ignition in rolling stock.
- To analyze the physicochemical characteristics of the combustion process and the spread of smoke in the confined spaces of tunnels.
- To examine and evaluate the existing technical fire safety systems in the tunnel infrastructure of the Republic of Bulgaria.
- To propose specific, scientifically and practically justified guidelines for optimizing the operational-tactical actions of the GDPBZN teams in liquidating such complex accidents.

The development of the topic in the report has direct practical significance for increasing security in the railway sector and for preserving the highest value - human life.

In order to build an effective system for the prevention and management of crisis events in the railway sector, it is first necessary to define and classify the events. According to the current regulatory requirements of the EU and the corresponding national regulatory framework (Regulation No. 15 on the investigation of railway accidents), events affecting the safety of railway transport are divided into several main categories:

Abnormal phenomena and technical malfunctions: Any violation of operating standards or the occurrence of defects in the rolling stock and infrastructure, which at the time of their occurrence did not lead to disruption of traffic or damage, but carry a potential risk.

Incident: Any event that negatively affects the safety of rail transport and is related to the operation of trains but does not meet the criteria for an "accident" (e.g. signalling failure, sudden stop or technical failure of a locomotive in motion).

Accident: An unwanted or unforeseen sudden event or a specific chain of such events that has harmful consequences (collision, derailment, fire or explosion).

Serious rail accident: Any incident involving at least one moving railway vehicle resulting in the death of at least one person, at least one seriously injured person, or significant damage to rolling stock, track, other facilities or the environment, estimated at more than EUR 150,000.

Major rail accident: An event where the amount of material damage, according to the assessment of the investigating authorities, amounts to at least BGN 4 million.

The categorization of accidents according to their direct physical nature includes:

Collision between rolling stock (head-on, overtaking or side).

The analysis of the state of railway safety in Europe (based on aggregated data from the European Railway Agency ERA) shows relatively stable levels of safety, but at the same time highlights specific trends. Thousands of accidents have been registered in the EU Member States over a long period of time. The aggregated data on typical accidents show the following percentage ratio:

- Derailments: ~31.7%
- Level crossing accidents: ~20.5%
- Train collisions: ~16.5%
- Fires in rolling stock: ~4.8%
- Other types of accidents: ~26.5%

Although fires account for less than 5% of the total statistics, their destructive potential and media and public response are enormous. There are several iconic tunnel fires in world history that rewrote safety rules:

Hokuriku Tunnel Fire, Japan (1972): A fire broke out in the cafeteria of the overnight train "Kitaguni" passing through the nearly 14 km long Hokuriku Tunnel. The driver stopped the train inside the tunnel in accordance with the instructions at the time. This turned out to be a fatal mistake. In the confined space, the lack of ventilation led to a rapid accumulation of carbon monoxide and thick smoke. 30 people died (most of them from suffocation), and hundreds were injured. This tragedy fundamentally changed Japanese and global emergency rules: it was accepted as an ironclad rule

that in the event of a fire, the train should do everything possible to continue its movement and get out of the tunnel, instead of stopping in it.

Channel Tunnel fires (1996, 2006, 2015): These incidents (mostly in shuttles carrying freight trucks) demonstrate how critical automatic systems are. Despite the enormous smoke and high temperatures, thanks to modern ventilation systems that create overpressure in the parallel service tunnel, there were no casualties. These cases proved the effectiveness of modern rescue concepts in long tunnels.

Analysis of railway accidents in the Republic of Bulgaria

In Bulgaria, the situation differs radically from the average European statistics and raises serious concerns. For the period 2006 - 2023, 62 serious railway accidents were registered.

Their distribution by type shows the following critical picture:

- Derailments: 25 cases (~40.3%)
- Fires in rolling stock: 24 cases (~38.7%)
- Level crossing accidents: 7 cases (~11.3%)
- Train collisions: 4 cases (~6.4%)
- Other: 2 cases (~3.3%)

Critical conclusion: In Bulgaria, the share of fires (nearly 39%) is almost eight times higher than the average for Europe (~4.8%). This is due to systemic problems - outdated rolling stock (locomotives series 40, 43, 44 over 35-40 years old), depreciated electrical installations, lack of automatic fire alarm systems in older passenger cars and delayed renewal of the fleet.

Analysis by time and seasonality in Bulgaria

Seasonal dependence: A statistical peak in fires is observed in the months of June, July and August. High atmospheric temperatures in combination with the maximum load on the traction motors and the braking systems of the locomotives often lead to overheating of the engine rooms and ignition of oils and cable insulation.

Time zones: The most risky intervals are in the afternoon and early evening hours (16:00 - 20:00), which coincides with both the temperature peak of the day and the busiest train schedule.

The tragedy on the Sofia - Kardam train (February 28, 2008):

This incident is the blackest point in the recent history of BDZ and a starting point for all modern discussions on fire safety in our country. The fire broke out shortly before midnight in the couchette car of the night fast train in the area of Cherven Bryag station. The flames quickly spread to the neighboring sleeping car. As a result of the toxic gases and high

temperature that developed in a matter of minutes, 9 people died, their bodies charred beyond recognition. The investigation showed that the causes lie in complex factors – from technical malfunctions to incorrect actions of the staff. The tragedy proved in the most painful way how quickly fire spreads in passenger cars and how vital an immediate and organized evacuation is. If a similar incident had occurred in a long tunnel (for example, "Koznitsa"), the scale of the tragedy would have been unpredictable.

The railway infrastructure in the Republic of Bulgaria is managed by the State Enterprise "National Railway Infrastructure Company" (SE NRIC) and represents a complex complex of linear and point objects. Currently, the total deployed length of the railway network in the country amounts to approximately 6,446 km. It includes main railway lines, secondary branches, station tracks and specialized industrial lines.

Electrification is a key factor for assessing fire risk:

- Over 70% of the national network is electrified.
- A standard alternating current system with a voltage of 25 kV and a frequency of 50 Hz is used.
- Power is supplied through an overhead contact network supported by traction substations.

Specifics of the fire risk on electrified routes: The presence of high voltage of 25,000 V in close proximity to the rolling stock poses enormous challenges to rescue teams. In the event of a fire or derailment, the first and absolutely critical action for the safety of firefighters is the guaranteed disconnection of the voltage in the contact network and its physical grounding by authorized railway personnel. Any supply of water or other extinguishing agent before grounding poses a deadly risk of electric shock from the extinguishing jet.

Characteristics of the tunnel network and analysis of its condition

Tunnels are the most expensive, complex and at the same time the most risky elements of the railway infrastructure. A total of 186 railway tunnels with a total length of about 47.9 km operate in Bulgaria. They are unevenly distributed along the rugged mountainous terrain in the country.

The analysis of the age structure and technical condition of the existing tunnel fund in our country raises serious concerns among fire safety experts: about 65% of the operating tunnels were designed and built in the first half of the 20th century (many of them even before World War II).

These facilities were built according to old construction standards, without taking into account modern fire and emergency safety requirements. Only a minimal number of tunnels have undergone a complete

technical modernization in recent decades. The distribution of existing tunnels by length is as follows:

- Up to 50 m: 20 units.
- 50– 100 m: 39 units.
- 100– 200 m: 54 units.
- 200– 500 m: 53 units.
- 500 – 1000 m: 12 units.
- Over 1000 m (long tunnels): 6 units.

The longest operating railway tunnel in the country is "Koznitsa" (5,812 m long), located on the Podbalkanska railway line and connecting the Stara Planina with the Sashtinska Sredna Gora. The second longest is the "Galbets" tunnel (3,034 m).

Safety problems in old tunnels

Most of these facilities do not have built-in systems for forced smoke extraction, there are no emergency exits (evacuation galleries), there is no reliable working and emergency lighting, as well as dry fire pipelines for water supply. In the event of a fire in a tunnel like "Koznitsa", the evacuation of passengers would be extremely difficult due to the huge distance to the portals in conditions of thick and suffocating smoke.

Future projects, new construction and modernization

With the introduction of the European directives for interoperability and in compliance with the requirements of Regulation No. 55 INSTRUCTIONS FOR ROUTINE MAINTENANCE OF RAILWAY ..., a fundamentally new approach is being applied in Bulgaria in the design of underground railway facilities. Large-scale new facilities are being implemented and designed on the Sofia – Plovdiv and Sofia – Pernik – Radomir routes. ANNUAL PROGRAM - NRIC:

Project "Elin Pelin – Kostenets" (Tunnel 8): The longest railway tunnel ever built in Bulgaria and the Balkans is being built in this section, with a length of 6.8 km. Plovdiv: railway section Elin Pelin – Kostenets - NRIC. It is being built using a modern tunnel method and will meet the strictest European fire safety criteria.

Project "Ihtiman – Septemvri": It envisages the construction of modern single-tube double-track tunnels. For all facilities with a length of over 1000 m, the following are set:

- Specialized vertical evacuation shafts or parallel galleries.
- Transverse or longitudinal ventilation to create controlled overpressure to prevent smoke from entering the evacuation routes.
- Water supply systems for fire extinguishing.

- Vladaya Tunnel (Project Proposal): Designed as a massive two-tube tunnel with a length of 4820 m and 4754 m respectively. The safety concept includes:
- Cross connections (galleries) between the two tubes for safe evacuation every 150 to 250 m.
- Construction of specialized rescue zones in front of the portals and a landing pad for helicopters for emergency medical assistance.
- Installation of a dry fire pipeline with installed fire cabinets with hoses and nozzles every 125 m along the length of the tunnel.

Regulatory requirements for new facilities. All new railway tunnel projects over 1000 m long must undergo the preparation of a detailed "Fire Safety Concept". It includes computer simulation of fire development and passenger evacuation, proving the stability of the tunnel lining at high temperatures and ensuring access for fire trucks.

Successful fire control in rolling stock depends on seconds and requires impeccable coordination between the train crew, dispatch centers and territorial bodies of the General Directorate for Fire Safety and Population Protection (GDPBZN). The elimination of such accidents is subject to a specific algorithm of operational-tactical actions, divided into several critical stages.

Initial actions of locomotive and vehicle personnel: the train crew is the first echelon of response and the lives of dozens or hundreds of passengers depend on their actions in the first 5 to 10 minutes.

*Early detection and signaling: w*hen a sensor from the automatic fire alarm system (if any) is activated or when smoke and flame are visually detected, the personnel are obliged to immediately localize the source.

The driver or train conductor immediately transmits a message to the train dispatcher via the GSM-R radio station or via a mobile connection. A signal is also sent to the Single European Emergency Call Number 112. The message must contain: train number, exact location (kilometer along the railway line), nature of the fire (locomotive or wagon) and presence of people at risk Fire Action Plan - Fire Safety for.

Making a tactical decision to stop. Golden rule: If the fire occurs while moving in a tunnel, the driver must do everything possible to take the train out of the tunnel into open space. Stopping a burning train in the tunnel is a last resort measure that is only allowed in the event of a technical impossibility of continuing the movement (for example, blocking the brakes or complete loss of traction). Actions after stopping the train (outside the tunnel or in case of forced stopping inside):

Shutting off the traction current and removing the pantographs (pantographs) of the locomotive.

Use of portable powder or carbon dioxide fire extinguishers available in the locomotive and carriages to control the flames in their initial phase Rules for action in the event of a fire.

In the event of a fire in a carriage, the unaffected part of the train is immediately disconnected in order to limit the spread of the fire, if conditions allow.

*Evacuation of passengers: c*onductors and transport personnel organize the rapid and panic-free evacuation of passengers Rules for action in the event of a fire. The direction of evacuation in a tunnel is determined depending on the movement of smoke - people always head against the air current (towards the smoke-free portal) or towards the nearest emergency exit.

Operational and tactical actions of the GDPBZN teams: after receiving the signal at the Regional PBZN Service, specialized vehicles are sent to the site. Firefighting actions are developed according to the following tactical plan:

Reconnaissance and assessment of the situation: The head of the operation establishes contact with the train dispatcher and station staff to obtain confirmation that the contact network in the area is disconnected and grounded. The exact location of the train, the number of carriages, the degree of smoke and the presence of trapped people are determined.

Deployment of forces and resources: in the event of incidents in tunnels, two or more penetration groups are formed - if possible from both tunnel portals simultaneously, in order to carry out a "pincer" containment of the fire and search for victims. Firefighters must use self-contained breathing apparatus with compressed air (SCBA), since in the closed underground space the concentration of toxic combustion products (carbon monoxide, hydrogen cyanide from plastics) is deadly.

Fire containment and extinguishing: Powerful water jets (compact and atomized) or air-mechanical foam are used to extinguish fires in rolling stock, especially if engine oils and fuels in diesel locomotives are burning.

If there is a dry pipe installation in the tunnel, it is supplied with water from the fire engines located in front of the portal. STRATEGY FOR IMPLEMENTING THE TSI "SAFETY .... In the absence of such, the hose lines are deployed manually along the track, which requires significant physical effort and time.

Providing ventilation: Managing smoke flows is a key element of the tactic. If the tunnel has forced ventilation, it is switched on in a mode that

"pushes" the smoke away from the passenger evacuation zone and the fire brigade's advance. Mobile high-flow fans located at the portals are also used to create a directed air flow.

Communication and interaction: a critical point for the failure or success of the operation is communication. Radio communication in underground facilities fades extremely quickly. For this reason:

Special portable repeaters or leaky feeder systems built into the modernized tunnels are used. STRATEGY FOR IMPLEMENTATION OF THE TSI "SAFETY ....

Liaison officers are appointed over a certain distance to transmit messages along the chain from the inside of the tunnel to the external headquarters. This information proves that without previously played out scenarios and agreed operational plans between the National Railway Infrastructure Company (NRI) and the structures of the Ministry of Interior-GDPBZN, the elimination of a fire in a railway tunnel would be accompanied by a huge risk of serious human casualties.

Peculiarities of fire extinguishing in tunnels: fires in railway tunnels are fundamentally different from those in standard above-ground buildings and facilities. They occur in conditions of highly confined space, with the physico-chemical processes of combustion developing with extreme speed and intensity. Controlling such accidents requires excellent knowledge of the dynamics of closed fires and the specific factors of the tunnel environment.

Physico-chemical processes in combustion in a tunnel environment: the combustion process in a tunnel is directly influenced by the geometry of the underground facility and the lack of oxygen. In these conditions, the following specific phenomena are observed.

Extreme thermal load and temperature curve: due to the lack of free heat exchange with the atmosphere, the heat released during combustion accumulates in the tunnel tube. The temperature in the convective column above the fire source increases in an avalanche-like manner.

Instead of the standard temperature curves for buildings, in tunnel fires the temperature development follows accelerated curves (such as the internationally recognized RWS curve or the hydrocarbon curve), in which values of 1000°C to 1200°C are reached in less than 5 to 10 minutes.

This thermal load causes the destruction of the concrete lining of the tunnel (the so-called "explosive spalling" of the concrete) and threatens the load-bearing capacity of the structure.

Chimney effect and smoke flows. Gases heated to a high temperature have a significantly lower density than the surrounding cold air. This

creates a powerful lifting force. In tunnels with an inclination, the so-called "chimney effect" occurs—smoke and flames are directed at a speed of several meters per second towards the higher portal, turning the tunnel into a giant smoke pipe.

Incomplete combustion and high toxicity: since the flow of fresh air is severely limited, the combustion process quickly switches to an oxygen deficiency mode.

This leads to incomplete combustion of the materials and the release of huge amounts of carbon monoxide, thick black smoke and soot. When burning plastics, polyurethane foam (foam in the seats) and cable insulation, the highly toxic gas hydrogen cyanide is released, the concentration of which in a closed environment exceeds many times the lethal doses for humans.

Specific problems for the PBZN authorities. The localization and elimination of a fire in a railway tunnel poses a number of critical problems for the GDPBZN teams that have no analogues in other types of accidents:

The phenomenon of the “reverse layer” (Backlayering): When smoke moves under the ceiling of the tunnel against the direction of the firefighters’ advance or against the direction of the ventilation. It seriously threatens the evacuation routes and blocks the visibility of the rescue teams.

Difficult orientation and visibility: in conditions of thick and toxic smoke, visibility drops to zero. Firefighters have to navigate by feeling the rails or walls of the tunnel.

Physical and psychological overload: deploying hose lines over distances of hundreds of meters or kilometers in a smoky environment requires enormous physical effort. Wearing self-contained breathing apparatus limits the working time of one team to about 30–40 minutes, which requires organizing frequent team changes.

Modern technical solutions for risk management. To minimize these risks, the modern design and modernization of railway tunnels in Bulgaria rely on the implementation of innovative systems:

Water mist systems (WMS): unlike traditional sprinkler systems, water mist systems use a minimal amount of water, sprayed under high pressure in microscopic drops. This leads to rapid cooling of the tunnel space, absorption of smoke particles and localization of the fire, without causing major damage to the electrical infrastructure.

Longitudinal and transverse ventilation: ventilation systems in modern tunnels are designed to create a controlled air flow velocity (typically between 1.5 and 3 m/s) in the event of a fire, which will stop the “reverse

layer" effect and push the smoke in a controlled direction, leaving clean air for evacuating people and advancing firefighters.

Evacuation and rescue galleries: all new tunnels over 1000 m long are equipped with transverse connections to a parallel pipe or specialized emergency galleries. They are equipped with doors with a high degree of fire resistance and overpressure systems that ensure that smoke does not penetrate them.

Understanding these complex processes is key to developing adequate tactics by firefighting operations managers.

Conclusion

The research conducted within the framework of this report categorically proves that fire safety in railway transport, and in particular in the case of incidents in the tunnel network, is an extremely complex and multilayered problem. Railway tunnels are specific linear underground facilities, which in the event of a fire drastically change the dynamics of classical fire extinguishing.

The analysis of the state of the railway infrastructure in the Republic of Bulgaria and the comparison with international experience outline several fundamental conclusions:

Critical specificity of national statistics: In Bulgaria, the share of fires in rolling stock (nearly 39% of all serious accidents) is disproportionately high compared to the average European levels of about 4.8%. This turns the fire hazard in railways into a real problem of national security.

Obsolete existing stock: The majority of the currently operating 186 railway tunnels were built decades ago. They suffer from a lack of modern evacuation and fire-fighting systems, which puts passengers and rescue teams at increased risk in the event of an incident.

Extreme environment: The physical and chemical processes of tunnel fires (the chimney effect, the inverse layer phenomenon, the avalanche-like rise in temperature above 1000°C and the release of highly toxic gases) require specific tactical training and high-tech equipment for the GDPBZN teams.

Progress in new construction: The new projects implemented along the European transport corridors demonstrate a fundamentally different and modern approach. They implement the highest safety standards set out in the Transport Specifications for Interoperability (TSI), including ventilation systems, emergency exits and dry fire pipelines.

Recommendations for optimizing safety

Based on the scientific-applied and statistical analysis performed, the following recommendations are proposed to increase the level of fire safety and improve the effectiveness of operational-tactical actions:

Regarding the regulatory framework and prevention

Harmonization of norms: Continue the strict implementation and adaptation of the European tunnel safety directives to the national regulatory framework (Regulation No. 55, etc.).

Mandatory risk assessments: Introduce a requirement for periodic updating of risk analyses for all existing (old) tunnels with a length of over 1000 m.

Regarding railway infrastructure and rolling stock

Modernization of old tunnels: Phased equipment of longer existing tunnels with autonomous emergency lighting, clear phosphorescent marking for the evacuation direction and dry fire extinguishing pipelines.

Renewal of the traction stock: Acceleration of the process of replacement and complete rehabilitation of obsolete locomotives with depreciated electrical installations, as they are the main source of fires in Bulgaria.

Automatic notification: Equipping all passenger cars operating on the national network with modern automatic fire alarm systems, connected directly to the driver's cabin.

Regarding operational-tactical actions

Specific equipment: Providing regional PBZN services, in whose areas there are long railway tunnels, with specialized equipment (isolating breathing apparatus with extended operating time, portable thermal imaging cameras and mobile powerful fans).

Development of communications: Implementation of secure underground radio communication systems (radiating cables), ensuring uninterrupted connection between internal teams and external headquarters.

Joint practical exercises: Conducting annual large-scale simulations and practical exercises on the territory of the long tunnels with the participation of SE NRIC, BDZ and MV-GDPBZN to practice the real coordination of actions.

References:

1. Law on the Ministry of Internal Affairs
2. Law on Railway Transport
3. Reference document of the railway network 2023-2024

4. Ordinance No. 58 of August 2, 2006 On the rules for technical operation, train movement and signaling in railway transport
5. Ordinance supplementing Ordinance No. 58 of August 2, 2006
6. Norms for the design of road and railway tunnels of January 1, 1989
7. Ordinance No. 55 of January 29, 2004 On the design and construction of railway lines, stations, level crossings and other elements of the railway infrastructure
8. Ordinance No. 59 of December 5, 2006 On safety management in railway transport
9. Ordinance No. 51 of January 3, 2002 on the requirements for technical operation of the railway infrastructure (Repealed SG No. 73/2006)
10. Rules for the activities of the Directorate for Fire and Emergency Management - Ministry of Internal Affairs in registering and reporting fires, disasters and emergencies
11. Ordinance No. RD-02-20-2 of 21.12.2015 on technical rules and norms for the design of road tunnels
12. EU Regulation No. 1303/14 on the technical specification for interoperability with regard to "safety in railway tunnels" of the European Union railway system
13. Disaster Protection Act
14. Assoc. Prof. Dr. Eng. Zhani Neykova, Railway Fire Extinguishing Installations tunnel 2 on the Vidin – Medkovec lineModernization of the Sofia – Plovdiv railway line: railway sections Sofia - Elin Pelin and Elin Pelin - Septemvri" for the Ihtiman – Septemvri section
15. Instructions for the operation of the train dispatching apparatus in the "Train Traffic Management and Station Activity" division of the "Train Traffic and Capacity Management" division of the State Enterprise "NRIC"
16. https://www.mtc.government.bg/bg/category/183
17. https://www.mtc.government.bg/archive/page.php?category=390&id=2569&page=4
18. https://www.mlit.go.jp/jtsb/railrep.html
19. https://fan.bdz.bg/bg/istoria/category-istoria.htm
20. https://assets.publishing.service.gov.uk/media/572b0031ed915d1452000000/160505_ReportET2016_eurotunnel_eng.pdf
21. https://www.tunnel-online.info/download/422077/2012_01_Fixded_Fire_Fighting_Systems.pdf

THE INNOVATIVE IDEAS COMPETITION: FOSTERING KNOWLEDGE EXCHANGE AND ENTREPRENEURIAL SKILLS DEVELOPMENT

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Education 5.0

Abstract: *The study presents a comparative analysis of four consecutive editions of the Solve for Tomorrow competition in Bulgaria (2022–2026), combining qualitative and descriptive quantitative analysis. It examines participation dynamics, the characteristics of student ideas, and the educational value of the competition. The results indicate expanded participation and changes in the formulation of student ideas, including more clearly defined problems, target groups, and opportunities for practical application. The analysis also identifies multiple channels for knowledge exchange among students, teachers, mentors, experts, and professional communities. The findings suggest that the educational value of an innovation competition is related not only to its competitive format but also to the educational environment surrounding it, including training, design thinking, mentoring, collaboration, and knowledge exchange.*

Keywords: *Solve for Tomorrow, entrepreneurial competences, design thinking, STEM, knowledge exchange, educational environment*

1. Introduction

Social, economic, and technological changes place increasing demands on education to develop knowledge, skills, and attitudes that enable young people to address complex real-world problems and develop solutions to them. Innovation competitions can complement formal education by providing opportunities to apply knowledge in practical situations and to develop creativity, critical thinking, collaboration, and entrepreneurial initiative.

Student innovation and entrepreneurship are promoted through different forms, including idea competitions, student enterprises, and other practice-oriented initiatives. In Bulgaria, such activities are implemented by public institutions, private organizations, civil society organizations, and academic institutions in formal and non-formal educational settings (Delinesheva & Jolovski, 2021).

An international initiative using the competition format to engage students with real-world challenges is Solve for Tomorrow by Samsung Electronics. Launched in 2010, the initiative has expanded internationally and has reached 2.9 million students in 68 countries. Its main format is a competition for developing technology-based solutions to real-world problems, drawing on STEM knowledge and design thinking.

In Bulgaria, Solve for Tomorrow has been implemented since 2022 in partnership with the Education 5.0 Foundation, which participates in the organization of the competition and related educational activities. A distinctive feature of the Bulgarian implementation is the extension of the competition through teacher training, practical workshops on design thinking, and mentoring support.

The aim of this study is to analyse four consecutive editions of Solve for Tomorrow in Bulgaria (2022–2023, 2023, 2024–2025, and 2025–2026) in terms of participation, characteristics and development of student ideas, and the educational value of the competition. The analysis considers Solve for Tomorrow as an educational environment for knowledge exchange and the development of entrepreneurial competences.

2. Conceptual Framework

Innovation competitions can complement formal education by providing opportunities to work on real-world problems, apply knowledge, and develop innovation-related skills. Research on innovation competitions identifies their potential as learning environments in which participants develop problem-solving, creativity, collaboration, and practical application of knowledge (Konak et al., 2024; Song & Zhu, 2025).

These characteristics correspond to experiential learning and project-based learning, which emphasize active participation, authentic tasks, and reflection (Kolb, 1984; Thomas, 2000). Experiential learning has also been discussed in Bulgarian research as an appropriate approach to entrepreneurship education and the development of entrepreneurial attitudes and skills, including idea generation and innovation (Ruseva et al., 2024).

The European Entrepreneurship Competence Framework (EntreComp) defines entrepreneurship as the capacity to act upon opportunities and ideas to create value for others. Its fifteen competences are organized into three areas: Ideas and Opportunities, Resources, and Into Action (Bacigalupo et al., 2016). Innovation competitions can activate competences from all three areas through problem identification, idea development, resource mobilization, collaboration, and presentation of solutions.

Another relevant dimension is knowledge exchange. Learning occurs through interaction among students, teachers, mentors, university lecturers, experts, and other participants. Wenger (1998) conceptualizes learning as participation in shared practice, while Nonaka and Takeuchi (1995) emphasize interaction as a mechanism for knowledge creation and transformation.

Innovation projects may require knowledge from several fields. Integrated STEM education connects science, technology, engineering, and mathematics and provides opportunities to apply knowledge from these fields to practical problems. A meta-analysis of 124 K–12 studies identified associations between integrated STEM education and knowledge acquisition, cognitive skills, and problem-solving (Chen et al., 2026).

Design thinking provides a human-centred process for understanding needs, defining problems, generating ideas, prototyping, testing, and refining solutions (Brown, 2008). Its relevance has also been discussed in STEM education and entrepreneurship education, particularly in relation to interdisciplinary learning, teamwork, problem-solving, and entrepreneurial thinking (Tan et al., 2026).

These perspectives provide the conceptual basis for examining the competition as a combination of experiential learning, entrepreneurial competence development, knowledge exchange, STEM integration, and design thinking.

3. Methodology

The study uses a comparative analysis of four consecutive editions of the Solve for Tomorrow competition in Bulgaria (2022–2026), combining qualitative and descriptive quantitative analysis. The comparison examines participation dynamics, the characteristics and development of student ideas, and educational activities associated with the competition.

The quantitative analysis includes data on project ideas, participating students and teachers, teams, and educational activities. The qualitative analysis is based on thematic examination of student ideas and the characteristics of educational activities across the editions.

The analysis is structured around three dimensions:

- Participation dynamics – participating students, teachers, teams, and educational institutions;
- Characteristics of submitted ideas – thematic focus, use of technology, social relevance, and alignment with competition categories;

- Educational value – training, workshops, mentoring, partnerships, knowledge exchange, and opportunities for developing entrepreneurial competences.

The results are interpreted through the theoretical perspectives presented in the conceptual framework. The study does not assess the quality of individual projects; rather, it identifies trends in participation, student ideas, and the educational opportunities associated with the competition.

4. Results and Discussion

4.1. Participation Dynamics

The Solve for Tomorrow competition was launched in Bulgaria in 2022 for students in Grades X–XII. In 2023, participation was extended to students in Grades II–VIII, divided into two age groups. Participation of the younger students was conducted online.

Across the four editions, students in the main age category submitted 326 project ideas, developed by 917 students with the support of 212 teacher team leaders. The number of teams increased from 73 in the first edition to 90 in the fourth, an increase of approximately 23%. Student participation increased from 204 in 2022–2023 to 306 in 2025–2026, or approximately 50%.

Students in Grades II–VIII submitted 55 ideas between 2023 and 2026, involving 204 students and 36 teacher team leaders. The number of ideas was 22 in 2023, 14 in 2024–2025, and 19 in 2025–2026.

The number of teacher team leaders in the main age category was 64, 51, 45, and 52 across the four editions. Thus, student and team participation increased while the number of teacher team leaders fluctuated within a relatively narrower range.

The competition involved secondary schools, vocational and specialized high schools, special schools, and educational centres. The number of unique participating institutions ranged from 29 to 42. Secondary schools accounted for 48%, 39%, and 45% in three editions, while vocational high schools represented the largest share in the second edition, at 36%. Specialized high schools increased their share from 21% in the first edition to 33% in the third and fourth editions.

Overall, the data indicate expanded participation and involvement of different types of educational institutions. The quantitative data, however, do not in themselves provide evidence about changes in motivation or the quality of the educational effect.

4.2. Characteristics and Development of Student Ideas

Across the four editions, the main thematic emphasis remained on sustainability and socially significant issues, despite changes in the names and structure of the categories.

In 2022–2023, Environment and Climate accounted for 34 ideas (47%), Social Equality for 24 (33%), and Safety and Healthcare for 15 (20%). In 2023, Sustainability represented 42 ideas (52%), followed by Social Inclusion with 22 (27%) and Education with 16 (20%).

In 2024–2025, Sustainability accounted for 40 ideas (48%), Education for 19 (23%), Justice and Social Inclusion for 13 (16%), and Digital Financial Management for 11 (13%). In 2025–2026, Sustainability Through Technology accounted for 44 ideas (49%), Social Change Through Technology for 36 (40%), and Digital Finance for 10 (11%).

Across the four editions, sustainability-related ideas accounted for 160 projects (49.1%), social development and change for 145 (44.5%), and digital finance for 21 (6.4%). Among students in Grades II–VIII, social and educational issues represented the largest share, with 30 ideas (54.5%), followed by sustainability and environmental issues with 23 (41.8%) and digital finance with 2 (3.6%).

The project proposals also show changes in the formulation of problems and solutions. In earlier editions, some problems are outlined in general terms and the proposed solutions remain conceptual. In later editions, ideas more often address a clearly defined problem related to the needs of a specific target group. These characteristics correspond to elements of design thinking, including understanding needs, defining problems, generating ideas, prototyping, and testing solutions (Brown, 2008).

The projects also demonstrate interdisciplinary application of knowledge and STEM-related principles. From the perspective of EntreComp, later editions contain more clearly discernible elements related to identifying opportunities, determining needs, mobilizing resources, and considering implementation.

Overall, the comparison indicates continuity in the main thematic priorities alongside changes in the formulation and development of student solutions.

4.3. Educational Value of the Competition

Participation in Solve for Tomorrow provides opportunities to work on real-world problems, apply knowledge, and collaborate. In this respect, the competition extends learning beyond the traditional classroom and creates conditions for experiential learning (Kolb, 1984; Thomas, 2000).

Design thinking is an important component of this process, providing a structured approach to understanding needs, defining problems, generating ideas, prototyping, testing, and refining solutions (Brown, 2008; Liedtka, 2018). Its use is consistent with interdisciplinary and problem-oriented learning in STEM education (Tan et al., 2026).

The educational environment surrounding the competition includes 53 teacher training sessions involving 1,107 teachers, 6 regional workshops involving 406 students and 70 teachers, and online webinars involving 46 students. These activities provide opportunities to acquire and apply knowledge related to design thinking and innovation beyond the submission of project ideas.

The mentoring programme for finalists operates at a later stage of project development. Expert mentors provide feedback on problem definition, target groups, prototypes, feasibility, and final presentation. In this way, mentoring supports the refinement of selected solutions and the application of knowledge during project development.

Thus, the educational value of the competition is associated not only with the final project but also with the process of research, problem analysis, idea development, prototyping, feedback, and refinement.

4.4. Knowledge Exchange

Knowledge exchange is an important component of the educational environment surrounding Solve for Tomorrow. Students interact with teacher team leaders, expert mentors, university lecturers, business representatives, and other professionals. These interactions provide opportunities for sharing experience, receiving feedback, and refining project ideas.

Within student teams, participants combine knowledge, discuss alternatives, and make joint decisions. Teacher team leaders provide support during project development, while expert mentors contribute at a later stage. These forms of interaction correspond to the concept of learning through participation and shared practice (Wenger, 1998).

Teacher training and regional workshops provide another channel for knowledge exchange. The participation of 1,107 teachers in 53 training sessions and 406 students and 70 teachers in 6 regional workshops creates opportunities for interaction among participants from different schools. Two national webinars additionally involved 46 students.

Interaction with university lecturers, business representatives, and experts introduces perspectives beyond the school environment. Such interaction can support the refinement of ideas and consideration of their practical application and can be interpreted in relation to knowledge creation

through interaction and knowledge transformation (Nonaka & Takeuchi, 1995). Knowledge exchange also occurs between educational institutions through the sharing of project and pedagogical experience. The competition therefore provides multiple channels for interaction among participants with different knowledge, experience, and expertise.

5. Conclusion

The study examines four consecutive editions of the Solve for Tomorrow competition in Bulgaria between 2022 and 2026, focusing on participation, student ideas, and the educational environment surrounding the competition.

The results indicate expanded student and team participation, accompanied by involvement of different types of educational institutions. The submitted ideas maintain a consistent focus on sustainability and socially significant issues, while later editions demonstrate more clearly formulated problems, target groups, and opportunities for practical application. The projects also incorporate knowledge and skills from different fields, including STEM and entrepreneurship.

The analysis shows that the educational value of the competition is associated with activities extending beyond project submission and competition. Teacher training, regional workshops, design thinking, mentoring, and interaction with experts create opportunities for learning through action and application of knowledge in practical contexts. The EntreComp framework provides a basis for interpreting competences involved in identifying opportunities, developing solutions, mobilizing resources, and taking action (Bacigalupo et al., 2016).

Knowledge exchange represents another important dimension. Students, teachers, mentors, university lecturers, and professionals contribute different forms of knowledge and experience and interact throughout the development of projects. This corresponds to the understanding of learning as participation and shared practice (Wenger, 1998).

The research contribution lies in the comparative systematization of data from four consecutive editions of an innovation competition in the Bulgarian educational context. The analysis demonstrates the relationship between the competition format, associated educational activities, and opportunities for knowledge exchange.

The present study shows that the educational value of an innovation competition is related not only to its competitive element but also to the educational environment surrounding it, including training, mentoring, design thinking, collaboration, partnerships, and knowledge exchange.

References:

1. BACIGALUPO, M., KAMPYLIS, P., PUNIE, Y. and VAN DEN BRANDE, G., 2016. EntreComp: The Entrepreneurship Competence Framework. Luxembourg: Publications Office of the European Union. DOI 10.2791/593884.
2. BROWN, T., 2008. Design thinking. Harvard Business Review, Vol. 86, № 6, pp. 84–92. ISSN 0017-8012.
3. CHEN, C. et al., 2026. The effects of integrated STEM education on K12 students' achievements: A meta-analysis. Review of Educational Research, Vol. 96, № 2, pp. 619–668. DOI 10.3102/00346543251318297.
4. DELINESHEVA, M. and JOLOVSKI, J., 2021. Mapping report of initiatives in Bulgaria for adolescent skills development through innovation, social entrepreneurship and financial literacy. Sofia: UNICEF Bulgaria. ISBN 978-619-7307-17-7. Available from: https://www.unicef.org/bulgaria/media/10521/file/BGR-mapping-initiatives-youth-skills-development--report-ENG.pdf.
5. KOLB, D. A., 1984. Experiential Learning: Experience as the Source of Learning and Development. Englewood Cliffs, NJ: Prentice Hall. ISBN 9780132952613.
6. KONAK, A. et al., 2024. Enhancing student learning in innovation competitions and programs. European Journal of Engineering Education [online], Vol. 50, № 2, pp. 360–380. DOI 10.1080/03043797.2024.2394945.
7. NONAKA, I. and TAKEUCHI, H., 1995. The Knowledge-Creating Company. New York: Oxford University Press. ISBN 9780195092691.
8. RUSEVA, M., BALTOVA, S. and NIKOLOVA, A., 2024. Challenges to entrepreneurship education in high school: Interaction between formal and informal assessment. Pedagogy, Vol. 96, № 1s, pp. 73–86. DOI 10.53656/ped2024-1s.06.
9. SONG, Y. and ZHU, X., 2025. Science education via science and technology innovation competitions: Learning environment, learning processes, and the effectiveness of talent development. ECNU Review of Education, Vol. 8, № 4, pp. 1065–1086. DOI 10.1177/20965311241300539.
10. TAN, J. P.-L., KIDMAN, G. and NUGRAHA, M. G., 2026. Design thinking in K-12 STEM education: Transforming pedagogy and student outcomes. In: BARKATSAS, T., GOFF, A. and NG, C., eds. Exploring Cognitive, Affective, Design Thinking, Artificial Intelligence, Cybernetics and E-Learning Dimensions in Contemporary Education. Leiden: Brill, pp. 181–214. DOI 10.1163/9789004751736_009.
11. THOMAS, J. W., 2000. A Review of Research on Project-Based Learning. San Rafael, CA: Autodesk Foundation.
12. WENGER, E., 1998. Communities of Practice: Learning, Meaning, and Identity. Cambridge: Cambridge University Press. ISBN 9780521663632.

DIGITAL TWINS IN CRIMINAL PROCEEDINGS: EVIDENTIARY VALUE, CHALLENGES AND LEGAL FRAMEWORK IN INTERNATIONAL COOPERATION

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Abstract: *This study examines the role of digital twins in criminal proceedings, with a particular focus on their application in international cooperation. Digital twins are analysed not as traditional forms of evidence, but as a technological method for collecting and verifying evidence. The paper explores their potential to improve crime scene reconstruction, evidentiary analysis and cross-border coordination between competent authorities. At the same time, it identifies key legal and practical challenges related to admissibility, reliability, data protection and the protection of procedural rights, including victims' rights. Special attention is given to the current European legal framework and its limitations in addressing emerging technologies. The study argues for the need to develop clear legal rules and procedural safeguards to ensure the lawful and effective use of digital twins in criminal justice.*

Keywords: *digital twins; criminal proceedings; evidence; international cooperation; digital evidence; victims' rights; European Union*

1. Introduction

The rapid digitalisation of contemporary society and the continuous advancement of emerging technologies have profoundly transformed all areas of social and legal life. Among these innovations, digital twins have attracted significant attention due to their ability to create dynamic virtual representations of physical objects, processes and events, enabling real-time monitoring, simulation and analysis [8; 3].

Originally developed for industrial and engineering applications, digital twin technology has gradually expanded into new domains, including law enforcement and criminal justice. Within both national criminal proceedings and international judicial cooperation, digital twins offer opportunities for reconstructing criminal events, analysing complex

evidentiary material and improving coordination among competent authorities across different jurisdictions. Despite these developments, the legal implications of digital twins remain largely unexplored in Bulgarian legal scholarship and practice.

The increasing use of advanced digital technologies raises important questions not only regarding the effectiveness of criminal investigations and prosecutions but also concerning the protection of fundamental rights and freedoms. Particular attention must be paid to the rights of victims of crime, whose interests may be directly affected by the collection, processing and interpretation of digitally generated information. Consequently, there is a growing need for a comprehensive legal analysis of the impact of digital twins on the functioning of criminal justice systems at both national and international levels.

This study aims to examine the role of digital twins as a technological tool within international cooperation in criminal matters, focusing on both the opportunities they create for more effective fact-finding and the legal risks they may pose to the procedural rights of individuals, particularly victims of crime.

2. Digital Twins and the Law of Evidence in Criminal Proceedings

Digital twins are defined in the scientific literature as dynamic digital models of real objects, processes or events that are created and updated through data obtained from various sources for the purposes of analysis, simulation and prediction [5; 8; 3]. In the context of criminal proceedings, they create new opportunities for the reproduction of facts, the reconstruction of events and the verification of different hypotheses. In this regard, it is also necessary to take into account the development of electronic justice as part of the broader process of the digitalisation of justice, which creates the conditions for the introduction of new technological solutions in criminal proceedings, including within the framework of judicial cooperation in the European Union [12; 13]. Therefore, the present study advances the thesis that digital twins should be regarded not as evidence or evidentiary means, but rather as a new technological method for the collection and verification of evidence.

The concept of “digital evidence” is also well established in legal theory and is understood as information with evidentiary value that is created, stored or transmitted in digital form [1; 2]. Bulgarian law, however, does not contain a legal definition of this concept, nor does it clearly regulate its place within the system of evidence. According to the provisions of the Bulgarian Criminal Procedure Code (promulgated in State Gazette No. 86

of 28 October 2005, as subsequently amended, most recently SG No. 16 of 10 February 2026), physical evidence consists of material objects connected with the criminal offence (Articles 109 et seq. CPC), while evidentiary means serve to reproduce such objects through exhaustively listed forms such as photographs, video recordings, audio recordings, plans and diagrams (Article 125 CPC). This legal framework clearly outlines the boundaries of the existing evidentiary categories. Bulgarian judicial practice has likewise not yet developed an established legal approach to the use of such technological models, which are discussed in legal theory under the broader concept of "digital evidence" [20].

In my view, digital twins cannot be classified as physical evidence because they do not constitute the actual objects themselves, but rather their digital representation. Nor can they be equated with evidentiary means. Although they perform a similar function—namely, the reproduction of facts from reality—there is a significant difference between them. Traditional evidentiary means are static and capture a specific moment in time, whereas digital twins are dynamic, capable of continuous updating, and allow for analysis and simulation. Furthermore, digital twins cannot be classified as expert opinions because they do not represent the independent assessment of an expert witness. They may be used in the preparation of an expert report, but they do not in themselves contain an expert conclusion [7].

The foregoing leads to the conclusion that digital twins do not fit within any of the existing categories of evidentiary law. For this reason, they should be regarded as an **independent technological method for the collection and verification of evidence**, expanding traditional procedural instruments through the introduction of possibilities for simulation, reconstruction and multi-scenario analysis of the factual circumstances of a case [9]. Through their use, it is possible to achieve a more accurate reproduction of the circumstances, to test competing versions of events, and to analyse facts in a manner that is not possible through traditional evidentiary means.

From the perspective of the rights of victims of crime, the use of digital twins has a dual significance. On the one hand, they may contribute to a more accurate establishment of the facts and a more complete reconstruction of the circumstances of the case, which is in the interests of victims and supports the guarantee of their right to a fair trial under Directive 2012/29/EU [14]. On the other hand, there are risks associated with inaccuracies in the data used, the possibility of manipulation of digital models, or the misinterpretation of the results generated by them, all of

which may adversely affect the rights and legitimate interests of victims. For this reason, the use of digital twins should be accompanied by clear procedural safeguards ensuring their reliability, verifiability and transparency. In this sense, the need for the normative recognition of digital twins as an independent method for the collection and verification of evidence is justified not only by technological development but also by the requirements of effective protection of the rights of all participants in criminal proceedings. This approach is also consistent with current trends in European Union law aimed at strengthening procedural safeguards and the protection of victims' rights, including in the context of the digitalisation of criminal justice [17].

3. Practical Applications of Digital Twins in Criminal Proceedings

Digital twins can be applied in a number of practical situations within the framework of criminal proceedings.

First, they may be used for crime scene reconstruction through the creation of three-dimensional models that allow for a more precise reproduction of the environment in which the offence occurred. This assists both investigative authorities and courts in establishing the factual circumstances of the case [4].

Second, digital twins may be employed in the analysis of complex events, including road traffic accidents and crimes involving multiple participants, through the simulation of different scenarios. This creates opportunities for a more thorough examination and verification of competing evidentiary hypotheses [9].

Third, they may facilitate international cooperation by creating a shared digital environment for the exchange and visualisation of information among competent authorities in different States [20].

At the same time, the current legal framework does not provide for such a method. This creates a legal gap regarding the admissibility and use of digital twins in criminal proceedings and gives rise to the risk of inconsistent practice in the assessment of such evidentiary sources. Similar issues have also been addressed in the case law of the European Court of Human Rights, which has held that the admissibility of evidence must be assessed in light of its reliability and the possibility for the parties to challenge it effectively within the framework of a fair trial [19]. For this reason, the introduction of digital twins as a new evidentiary method cannot be achieved solely through the interpretation of existing law but requires explicit legislative regulation. In some legal systems, there is already a growing tendency towards the use of digital models in criminal

investigations, which demonstrates the need to adapt the Bulgarian legal framework accordingly.

In view of the above, a *de lege ferenda* proposal may be made for the explicit regulation of digital twins in the Bulgarian Criminal Procedure Code as a new method for the collection and verification of evidence. The legislator could provide that digital twins constitute investigative measures and/or judicial evidentiary actions and define them as digital, including three-dimensional and dynamic, models of objects, locations or processes created on the basis of data collected in the course of criminal proceedings and intended to contribute to the clarification of the circumstances of the case.

Such regulation should be accompanied by safeguards concerning the reliability of the data used, the transparency of the methods applied, and the possibility for the parties to participate in the creation and verification of the digital model. This is necessary because of the risk of creating inaccurate or manipulated digital models, which may lead to incorrect factual and legal conclusions. In this context, account should also be taken of the ongoing development of the European Union's regulatory framework on artificial intelligence, which will have a significant impact on the use of such technologies [17].

4. Risks and Challenges of Using Digital Twins in International Cooperation

Alongside their potential benefits, the use of digital twins in international cooperation in criminal matters raises a number of significant challenges related both to the legal framework and to technological limitations.

First, issues arise from the differences between national legal systems. The Member States of the European Union apply different standards regarding the admissibility of evidence and procedural safeguards, which may complicate the use of digital models in cross-border investigations [6]. The absence of uniform rules creates a risk of inconsistent treatment of similar situations and divergent practices in the assessment of evidentiary material.

Second, there are risks related to the protection of personal data. Digital twins are often based on large volumes of information, including sensitive data, which raises questions regarding compliance with the requirements of the General Data Protection Regulation (GDPR) [16], particularly the principles of data minimisation and purpose limitation [10]. This

necessitates a careful assessment of the scope and manner in which such technologies are used.

Third, consideration must be given to the risks associated with the reliability and transparency of the technologies employed. Digital twins are developed on the basis of algorithms and models that are not always fully transparent, which may make it difficult to verify how the results were generated and may call their reliability into question [8]. The issue of State liability arising from the use of such technological tools in criminal proceedings must also be addressed. Where inaccuracies in the data used, errors in algorithms, or a lack of transparency in the models exist, there is a possibility of violations of the procedural rights of participants in the proceedings, including victims of crime. This creates the need for clear regulation of liability for damage caused as a result of the use of digital twins [11].

Furthermore, there is a risk of errors or manipulation within digital models. Incorrectly entered data or the deliberate distortion of information may lead to inaccurate conclusions, which can have a direct impact on the fairness of the proceedings. In a cross-border context, these risks are amplified due to the difficulties involved in ensuring effective control and verification by all participating States. This, in turn, raises doubts as to whether the parties will be able to effectively challenge results generated through such technologies.

Finally, the use of digital twins may affect the procedural rights of participants in criminal proceedings, including the right to defence and the right to a fair trial. If the parties do not have a genuine opportunity to understand and challenge the manner in which a digital model has been created, this may result in procedural inequality and undermine the fairness of the proceedings [21].

In this regard, the implementation of digital twins in international cooperation should be accompanied by clear rules ensuring transparency, verifiability and the protection of fundamental rights. Only through the existence of such safeguards can their lawful and effective use in criminal proceedings be guaranteed.

5. Legal Framework and the Need for Further Development

At present, the legal framework of the European Union does not contain specific regulations governing digital twins. Nevertheless, a number of legal instruments have indirect relevance to their use in criminal proceedings. The absence of clear regulation creates not only theoretical but also practical difficulties concerning the admissibility of such

technologies, their evidentiary value, and the possibility of effective judicial oversight over their use. As a result, uncertainty arises regarding their application in specific criminal proceedings.

Directive 2014/41/EU [15] on the European Investigation Order regulates the collection and exchange of evidence between Member States. Although it does not expressly provide for the use of digital twins, the Directive establishes the procedural framework within which such technologies could be employed in cross-border investigations.

Particular significance must also be attributed to the General Data Protection Regulation (GDPR) [16], which imposes strict requirements regarding the processing of personal data, including the principles of lawfulness, proportionality and data minimisation. In the context of digital twins, these requirements are especially important, as such technologies are often based on substantial volumes of information, including sensitive personal data.

At the international level, consideration should also be given to the Budapest Convention on Cybercrime [18], which regulates the collection and use of electronic evidence. The Convention provides mechanisms for access to data in a cross-border context, thereby facilitating cooperation between States. However, it does not contain specific provisions addressing newer technologies such as digital twins.

Despite the existence of this regulatory framework, it does not adequately address the impact of emerging technologies. The lack of specific regulation concerning the use of digital twins creates legal uncertainty both with regard to their admissibility and to the control mechanisms governing their use. The protection of victims' rights must also be taken into account. Directive 2012/29/EU [14] establishes minimum standards on the rights, support and protection of victims of crime. The Directive guarantees the rights to information, participation and protection against secondary victimisation. The use of digital twins may have a dual impact on these rights. On the one hand, they may contribute to a more accurate establishment of the facts and a more effective reconstruction of the circumstances of the case. On the other hand, risks may arise from inaccurate data, a lack of transparency in the technologies employed, or the possibility of manipulation of digital models, all of which may adversely affect the rights and legitimate interests of victims.

In light of the foregoing, there is a clear need for further development of the legal framework at both the national and European levels. Clear rules should be established regarding the use of digital twins as a method for the

collection and verification of evidence, together with procedural safeguards ensuring their reliability, transparency and verifiability.

The question nevertheless remains open as to whether the existing procedural framework is capable of responding adequately to the dynamic development of such technologies.

6. Conclusions

Digital twins represent an innovative technological method with the potential to significantly improve the collection and analysis of evidence, as well as the efficiency of criminal proceedings and international cooperation in criminal matters. At the same time, they do not fit within the existing system of evidentiary law and give rise to significant challenges relating to their admissibility, reliability and control, as well as to the protection of the procedural rights of participants in criminal proceedings, including victims of crime. The absence of explicit legal regulation creates a risk of inconsistent practice and legal uncertainty, particularly in a cross-border context. For this reason, there is a need for further development of the legal framework at both the national and European levels through the formal recognition of digital twins as an independent method for the collection and verification of evidence, accompanied by clear safeguards ensuring transparency, verifiability and the protection of fundamental rights.

In this regard, the development of the legal framework should take into account both technological progress and the need to guarantee a fair and effective criminal justice process in the context of ongoing digitalisation.

References:

1. Casey, E. (2011). Digital Evidence and Computer Crime: Forensic Science, Computers and the Internet (3rd ed.). Academic Press.
2. Carrier, B., & Spafford, E. H. (2004). An event-based digital forensic investigation framework. Digital Investigation, 1(2), 147–154.
3. Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. IEEE Access, 8, 108952–108971.
4. Kassin, S. M., Dror, I. E., & Kukucka, J. (2015). The forensic confirmation bias: Problems, perspectives, and proposed solutions. Journal of Applied Research in Memory and Cognition, 4(1), 42–52.
5. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016–1022.

6. Mitsilegas, V. (2016). EU Criminal Law after Lisbon: Rights, Trust and the Transformation of Justice in Europe. Hart Publishing.
7. Pavlov, Hr. (2018). Problems in organizing forensic science expertise in Bulgaria. In: IV International Scientific and Practical Conference "Scientific and Practical Results in 2017. Prospects for Their Development", Dubai, UAE, 28 December 2017. World Science, No. 1 (29), 89–90.
8. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415.
9. van der Aalst, W. (2016). Process Mining: Data Science in Action (2nd ed.). Springer.
10. Voigt, P., & von dem Bussche, A. (2017). The EU General Data Protection Regulation (GDPR): A Practical Guide. Springer.
11. Ivanova, M. (2018). Отговорност на държавата за вреди, причинени на граждани в наказателния процес. Burgas: FLAT.
12. Ivanova, M. (2013). Electronic Justice in Criminal Cases. Юридически сборник на Бургаския свободен университет, т. XXX, 129–142.
13. Valkova, D. (2024). Нови правни инструменти за цифровизация на съдебното сътрудничество в Европейския съюз. De Jure, 2(29).
14. Directive 2012/29/EU of the European Parliament and of the Council of 25 October 2012 establishing minimum standards on the rights, support and protection of victims of crime.
15. Directive 2014/41/EU of the European Parliament and of the Council of 3 April 2014 regarding the European Investigation Order in criminal matters.
16. Regulation (EU) 2016/679 of the European Parliament and of the Council (General Data Protection Regulation – GDPR).
17. Regulation (EU) 2024/1689 of the European Parliament and of the Council (Artificial Intelligence Act – AI Act).
18. Council of Europe Convention on Cybercrime (Budapest Convention), 2001.
19. European Court of Human Rights, Schenk v. Switzerland, Judgment of 12 July 1988.
20. European Commission (2020). Communication on Digitalisation of Justice in the European Union.
21. Fair Trials (2021). Automating Injustice: The Use of Artificial Intelligence & Automated Decision-Making Systems in Criminal Justice in Europe.

DIGITAL TWINS AND HUMAN FACTORS: CAN AI PREDICT HUMAN ERROR?

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Abstract: *The increasing operational complexity of modern aviation systems requires more advanced approaches to safety management and human performance optimization. Although Safety Management Systems (SMS) and Human Factors frameworks have significantly improved aviation safety over recent decades, many existing models remain predominantly reactive or compliance-oriented. The prediction of human error before operational degradation occurs continues to represent a major challenge for the aviation industry. This paper explores the emerging role of digital twins, artificial intelligence (AI), neuro-agility, and predictive analytics in aviation safety management. It proposes a conceptual framework titled the Neuro-Adaptive Aviation Digital Twin Model (NAADTM), designed to integrate Safety Management Systems, Human Factors principles, neuro-cognitive adaptability, competency-based performance analytics, and AI-supported predictive safety intelligence into a unified human-centered aviation safety architecture. The proposed framework aims to support predictive identification of elevated human error risk, adaptive training strategies, and enhanced organizational safety resilience. The paper argues that future aviation safety systems may evolve from static and retrospective safety structures toward dynamic, adaptive, and predictive human performance ecosystems.*

Keywords: *digital twins, aviation safety, human factors, artificial intelligence, neuro-agility, predictive safety, SMS, aviation intelligence, human error prediction*

1. Introduction

Aviation represents one of the most complex socio-technical environments in modern industry. Despite major technological advances in aircraft systems, navigation technologies, automation, and operational procedures, human factors continue to contribute significantly to aviation incidents and operational risk exposure. Human performance variability, cognitive overload, fatigue, communication breakdowns, organizational pressure, and

decision-making limitations remain central challenges within aviation safety management.

The International Civil Aviation Organization (ICAO) defines Safety Management Systems (SMS) as a systematic approach to managing safety through organizational structures, policies, accountabilities, and procedures (ICAO, 2018). Modern SMS frameworks emphasize hazard identification, safety risk management, safety assurance, and safety promotion. However, despite the evolution from reactive toward proactive and predictive safety approaches, many operational systems still rely heavily on retrospective data analysis and post-event investigation.

At the same time, aviation organizations increasingly implement digital technologies such as artificial intelligence (AI), machine learning (ML), predictive analytics, and digital twins. In engineering applications, digital twins are already widely used for predictive maintenance, aircraft monitoring, operational optimization, and infrastructure management. Nevertheless, the application of digital twin technology to human performance and Human Factors management remains relatively underdeveloped. This paper proposes the Neuro-Adaptive Aviation Digital Twin Model (NA-ADTM), a conceptual framework integrating Human Factors, neuro-agility, aviation intelligence, AI-supported predictive analytics, and digital twin technologies into a predictive human-centered aviation safety ecosystem. The purpose of this study is not to replace existing SMS or Human Factors models, but rather to propose an adaptive framework capable of enhancing predictive safety capabilities through dynamic human performance analysis.

2. Literature Review

2.1 Human Factors and Aviation Safety

Human Factors research has long recognized that aviation safety depends not only on technological reliability but also on the interaction between human operators, organizational systems, operational environments, and decision-making processes. ICAO's SHEL model, later transformed into the SCHELL model, identifies the interaction between software, culture, hardware, environment, and liveware, including human-to-human operational interactions. These relationships illustrate the systemic nature of aviation safety and demonstrate that safety performance is strongly influenced by organizational culture, communication quality, leadership behavior, and cognitive adaptability.

Reason's Swiss Cheese Model (Reason, 1990) further demonstrates how organizational failures and latent conditions may align to produce

operational accidents. Similarly, the Human Factors Analysis and Classification System (HFACS) provides a structured framework for analyzing human error across multiple organizational levels. Crew Resource Management (CRM) programs additionally emphasize communication, situational awareness, teamwork, workload management, and operational decision-making as essential components of safe aviation operations.

Despite these advances, many traditional Human Factors approaches remain primarily retrospective, event-driven, and compliance-oriented. Existing models frequently focus on understanding why incidents occurred rather than predicting when operational degradation may emerge. Within contemporary safety theory, humans are increasingly viewed not only as potential sources of operational error, but also as critical sources of adaptability, resilience, recovery, and safety stabilization within complex sociotechnical systems. This perspective reflects the growing influence of resilience engineering and Safety-II philosophies, which emphasize understanding how aviation professionals successfully adapt to variability, operational pressure, and complexity under normal working conditions. As aviation systems become increasingly data-driven and operationally complex, there is growing recognition that future safety management requires more adaptive and predictive approaches capable of integrating dynamic human performance indicators. Recent ICAO Human Performance guidance further demonstrates a transition from traditional "human error" approaches toward systems-oriented and human-centered operational models. ICAO increasingly emphasizes that safety should focus not only on preventing error, but also on supporting human performance through organizational design, operational adaptability, and resilient systems thinking (ICAO, 2020).

2.2 Safety Management Systems and Predictive Safety

Modern Safety Management Systems have evolved considerably from purely reactive accident investigation methodologies. ICAO's Safety Management Manual (Doc 9859) emphasizes the importance of proactive hazard identification, predictive risk management, safety performance indicators, organizational learning, and Just Culture. Contemporary SMS frameworks increasingly integrate safety reporting systems, trend analysis, risk matrices, internal audits, safety assurance processes, and safety performance monitoring into organizational decision-making.

However, predictive capabilities remain limited in many operational environments due to the complexity and variability of human performance under operational stress. Current predictive safety systems continue to focus predominantly on operational trends, technical failures, maintenance

indicators, and historical incident databases. Although these systems significantly improve organizational safety awareness, they rarely incorporate dynamic neuro-cognitive and behavioral performance indicators capable of identifying early signs of human performance degradation.

This limitation becomes increasingly important in highly automated aviation environments, where human operators are expected to manage rapidly changing operational conditions, high cognitive workloads, and complex decision-making processes. Consequently, there is a growing need for safety models capable of integrating operational, psychological, behavioral, and neuro-cognitive dimensions into predictive safety management.

2.3 Digital Twins and Artificial Intelligence in Aviation

Digital twin technology refers to a dynamic virtual representation of a physical system continuously updated through operational data, analytics, and simulations. Within aviation, digital twins are currently used for aircraft systems monitoring, engine performance optimization, predictive maintenance, airport operations, and fuel infrastructure management. The integration of AI and machine learning enables digital twins to support anomaly detection, probabilistic forecasting, operational optimization, and predictive maintenance strategies.

Recent aviation studies increasingly investigate AI-supported Human Factors analysis, including machine learning approaches to Human Factors Analysis and Classification System classification, fatigue monitoring, and behavioral pattern recognition. The emerging field of neuroergonomics, which combines neuroscience, human factors, and operational performance analysis, further supports the development of adaptive systems capable of monitoring cognitive workload, fatigue, stress response, and situational awareness within complex operational environments. These developments demonstrate the growing potential of AI-supported predictive safety systems within aviation operations.

Nevertheless, current digital twin implementations remain predominantly technology-centered rather than human-centered. Unlike engineering digital twins, which primarily model technical systems and mechanical performance, human-centered digital twins must address dynamic cognitive, behavioral, emotional, and organizational dimensions. Human performance cannot be reduced to deterministic mechanical variables, as it is continuously influenced by stress, fatigue, communication, organizational culture, motivation, and operational context. Consequently, aviation human digital twins require adaptive and probabilistic rather than purely deterministic architectures. Aviation safety research has not yet fully developed a comprehensive framework capable of integrating cognitive

adaptability, stress resilience, behavioral variability, competency evolution, and neuro-cognitive indicators within a continuously evolving human performance digital twin architecture. This gap highlights the need for more integrated and adaptive human-centered safety models.

3. Research Gap

Although modern SMS and Human Factors systems have substantially improved aviation safety, several limitations remain evident. Many safety systems continue to operate primarily through retrospective analysis rather than dynamic prediction of human performance degradation. Traditional competency-based assessment systems frequently evaluate observable technical performance without adequately measuring cognitive flexibility, stress adaptation, emotional regulation, and neuro-cognitive resilience.

At the same time, current digital twin applications in aviation largely prioritize engineering systems over human-centered operational intelligence. Existing predictive safety frameworks rarely integrate neuro-agility, behavioral analytics, AI-supported cognitive assessment, and adaptive organizational learning within a unified conceptual model.

As a result, there remains a significant gap between existing operational safety systems and the emerging need for adaptive predictive human performance management. This gap creates the need for a dynamic, integrated, and human-centered framework capable of supporting predictive safety intelligence within complex aviation environments.

4. The Neuro-Adaptive Aviation Digital Twin Model (NAADTM)

4.1 Conceptual Foundation

The Neuro-Adaptive Aviation Digital Twin Model (NAADTM) is proposed as a multi-layered conceptual framework integrating Safety Management Systems, Human Factors, neuro-agility, aviation intelligence, predictive analytics, and digital twin technologies. The framework is designed to support predictive human performance assessment and operational safety optimization through continuous interaction between organizational, operational, cognitive, and behavioral dimensions.

Rather than functioning as a purely technological monitoring system, the proposed framework conceptualizes aviation safety as a dynamic interaction between human adaptability, organizational culture, operational complexity, and predictive intelligence. The model assumes that human performance variability is not static and therefore requires continuous adaptive assessment.

4.2 Operational SMS Foundation

The first layer of the model incorporates the traditional components of Safety Management Systems, including hazard identification, safety risk management, safety assurance, safety promotion, reporting systems, and Just Culture implementation. This layer provides the organizational safety infrastructure necessary for operational monitoring, accountability, communication, and risk governance.

Within the NAADTM framework, SMS is not viewed solely as a compliance mechanism, but as the foundational organizational environment through which predictive safety intelligence can emerge. The effectiveness of predictive systems depends heavily on organizational transparency, reporting culture, leadership support, and continuous operational learning.

4.3 Human Factors Layer

The second layer integrates Human Factors principles such as SCHELL interactions, CRM competencies, situational awareness, workload management, communication dynamics, fatigue, and operational decision-making. This layer recognizes that aviation safety is strongly influenced by the interaction between technological systems, organizational environments, and human adaptability.

Within this framework, Human Factors are treated not merely as post-event analytical tools but as continuously evolving operational variables. The model therefore emphasizes the importance of dynamic behavioral assessment and operational adaptability rather than static competency evaluation alone.

4.4 Neuro-Agility Layer

The third layer introduces neuro-agility as a dynamic operational capability reflecting an individual's capacity to adapt cognitively, emotionally, and behaviorally under changing operational conditions. Within the proposed framework, neuro-agility is reflected through indicators such as cognitive flexibility, stress resilience, emotional regulation, learning adaptability, fatigue tolerance, and behavioral consistency. The proposed framework does not assume simplistic deterministic interpretations of brain lateralization or cognitive functioning. Instead, neuro-agility is conceptualized as a multidimensional adaptive capability influenced by complex neuro-cognitive, behavioral, physiological, and environmental interactions.

This layer extends traditional competency assessment beyond observable technical performance toward adaptive neuro-cognitive performance under operational stress conditions. The model assumes that elevated human error probability may often emerge gradually through reduced

adaptability, cognitive overload, communication degradation, or emotional instability before observable operational failure occurs.

Consequently, neuro-agility may function as an important predictive indicator of operational performance degradation within complex aviation environments.

4.5 Aviation Intelligence Layer

The fourth layer introduces the concept of Aviation Intelligence, defined within this study as the integrated cognitive, operational, emotional, and strategic capability to perceive, assess, predict, and manage aviation risk within complex socio-technical environments.

The Aviation Intelligence layer integrates strategic decision-making, leadership behavior, organizational awareness, competency development, communication quality, and adaptive safety culture into a unified operational-cognitive capability. The model assumes that effective aviation safety does not emerge solely from procedural compliance, but from the continuous interaction between organizational intelligence, human adaptability, and operational awareness.

This perspective expands conventional safety thinking by positioning leadership behavior, communication dynamics, and organizational culture as active components of predictive safety performance rather than passive organizational characteristics.

4.6 Predictive AI Analytics Layer

The predictive analytics layer utilizes machine learning, behavioral analytics, trend analysis, probabilistic modelling, safety indicators, and predictive risk mapping to identify early signs of operational degradation and elevated human error probability. Within the proposed framework, neuro-agility and behavioral indicators may function as advanced leading safety indicators capable of identifying early signs of cognitive overload, stress-related degradation, communication instability, or reduced operational adaptability before observable safety events occur.

Potential data sources may include simulator performance, training results, competency assessments, incident reports, communication patterns, workload indicators, and behavioral trends. By integrating these datasets, AI-supported systems may eventually support more dynamic and individualized operational risk assessment.

Importantly, the proposed framework does not conceptualize AI as a replacement for human expertise. Instead, AI functions as a decision-support mechanism capable of identifying hidden operational patterns and supporting earlier intervention before significant performance degradation occurs.

4.7 Digital Twin Layer

The final layer creates a continuously evolving digital representation of the aviation professional. The digital twin may integrate operational performance, training progression, competency evolution, behavioral variability, neuro-cognitive indicators, communication dynamics, and predictive safety profiles into a dynamic adaptive model.

Importantly, the purpose of the digital twin is not surveillance or punitive evaluation. Instead, the framework is intended to support adaptive learning, personalized development, predictive safety support, and organizational resilience. Within this context, the digital twin becomes a developmental and preventive safety mechanism rather than a control instrument.

The proposed framework therefore positions the aviation professional at the center of the safety ecosystem, emphasizing continuous adaptation, operational resilience, and predictive support.

5. Discussion

The proposed NAADTM framework represents a conceptual transition from reactive safety management toward predictive and adaptive human-centered aviation safety. By integrating Human Factors, neuro-agility, AI-supported analytics, and digital twin technologies, the model attempts to bridge the gap between operational safety management and dynamic human performance prediction.

Potential organizational applications include pilot performance monitoring, competency-based training optimization, fatigue risk management, adaptive CRM programs, aviation leadership development, SMS enhancement, and predictive safety analytics. In practical application, NAADTM could support aviation organizations through integration with simulator assessment systems, competency-based training programs, safety reporting databases, fatigue risk management systems, and behavioral performance monitoring tools. Such integration may enable more individualized training interventions and earlier identification of elevated operational risk conditions. The framework may also support more personalized approaches to aviation training by identifying dynamic performance patterns and adaptive learning needs.

However, several important limitations and ethical considerations must be addressed. These include data privacy, algorithmic bias, psychological safety, transparency of AI decision-making, regulatory acceptance, and organizational trust. Human-centered implementation remains essential, as AI systems should support rather than replace professional judgment and

organizational responsibility. Ethical implementation represents a critical requirement for any AI-supported human performance framework. Predictive systems must avoid punitive interpretation of human variability and instead support psychological safety, organizational trust, and developmental learning environments. Human-centered governance and transparency therefore remain essential conditions for operational implementation.

Further empirical research is required to validate neuro-agility indicators, predictive performance metrics, operational applicability, and AI-supported human performance modelling within real aviation environments. Future studies may also explore the integration of biometric indicators, simulator-based behavioral analytics, and adaptive training systems into predictive aviation safety architectures. Additional empirical research may investigate potential correlations between neuro-agility indicators and operational safety outcomes, including communication quality, simulator performance variability, fatigue resilience, and adaptive decision-making under stress conditions.

6. Conclusion

The aviation industry is entering a new era in which digital twins, artificial intelligence, neuroergonomics, and predictive analytics may significantly reshape Human Factors and aviation safety management.

Although current SMS and Human Factors frameworks provide strong operational foundations, they remain limited in predicting dynamic human performance degradation before operational errors emerge. This paper proposed the Neuro-Adaptive Aviation Digital Twin Model (NAADTM), an integrated conceptual framework combining Human Factors, neuro-agility, aviation intelligence, AI-supported predictive analytics, and digital twin technologies to support predictive human-centered aviation safety.

The findings of this conceptual study suggest that future aviation safety architectures may progressively evolve toward adaptive and predictive human-centered ecosystems integrating artificial intelligence, neuro-cognitive analytics, and digital twin technologies. As aviation systems become increasingly data-driven and operationally complex, future safety management may depend not only on analyzing past failures, but on dynamically predicting and mitigating future human performance risks before incidents occur.

References:

1. Endsley, M. R. (1995). *Toward a theory of situation awareness in dynamic systems.* Human Factors, 37(1), 32–64.
2. European Human Factors Advisory Group (EHFAG). (2012). *European Strategy for Human Factors in Aviation.*EASA.
3. International Civil Aviation Organization (ICAO). (2003). *Human Factors Guidelines for Aircraft Maintenance Manual (Doc 9824).* ICAO.
4. International Civil Aviation Organization (ICAO). (2018). *Safety Management Manual (Doc 9859).* ICAO.
5. International Civil Aviation Organization (ICAO). (2020). *Manual on Human Performance for Regulators (Doc 10151).* ICAO.
6. Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). *Characterising the Digital Twin: A systematic literature review.* CIRP Journal of Manufacturing Science and Technology, 29, 36–52.
7. Parasuraman, R., & Hancock, P. A. (2001). Adaptive control of mental workload. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 305–320). CRC Press.
8. Parasuraman, R., & Rizzo, M. (Eds.). (2007). *Neuroergonomics: The Brain at Work.* Oxford University Press.
9. Reason, J. (1990). *Human Error.* Cambridge University Press.
10. Shappell, S. A., & Wiegmann, D. A. (2000). *The Human Factors Analysis and Classification System-HFACS.* FAA Office of Aviation Medicine.
11. Vermeulen, A. (2018). *NAP™ Training Manual: A Practical Guide to Understanding the NAP™ Brain Profile* (Version 1). Neuro-Link Practitioner Training Program.
12. Wiegmann, D. A., & Shappell, S. A. (2003). *A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System.* Ashgate Publishing.

INTEGRATING SUSTAINABILITY IN VET: NEEDS, PERSPECTIVES AND CHALLENGES

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Abstract: *The purpose of the paper is to assess sustainability incorporation into VET systems in Bulgaria, Italy, Romania, and Turkey through an analysis conducted in the framework of the Erasmus+ GreenTeach project, Reference Number: 2024-1-BG01-KA220-VET-000246431. Based on desk research, policy analysis, interviews with experts, and a survey of VET teachers, instructors, and educators, this paper presents the main challenges and needs in incorporating green competences, as well as possible ways to achieve this goal.*

Keywords: *Sustainability, Vocational Education and Training, Green competencies; Teacher professional development*

Introduction

The ecological and digital transitions have emerged as defining challenges for contemporary societies, significantly transforming labour markets, industrial processes, and educational systems. In response to climate change, environmental degradation, and increasing demands for sustainable economic development, Vocational Education and Training (VET) systems are increasingly recognised as strategic instruments for preparing a workforce capable of supporting the green transition. VET institutions play a critical role in "fostering sustainable development and equipping learners with the skills necessary for green and digital transitions".

Within the broader European policy framework, sustainability has become a central educational priority in VET reforms, in accordance with the Council of the European Union Recommendation on Vocational Education and Training from 24 November 2020 (European Union, 2020), the Osnabrück Declaration (CEDEFOP, 2020) and the European Sustainability Competence Framework "GreenComp" (European Commission, 2022) that promotes the integration of sustainability competencies into educational systems at all levels. In this context, the GreenTeach project (GreenTeach, n.d.) seeks to strengthen environmental sustainability and green

competencies within VET institutions by supporting teachers, modernising curricula, and promoting innovative pedagogical approaches.

The GreenTeach approach adopts a strategy that addresses multiple dimensions simultaneously, including teacher competencies, stakeholder collaboration, strategic planning, funding mechanisms, and curriculum transformation. This reflects the growing understanding that integrating sustainability cannot be achieved solely through isolated curricular modifications but requires systemic institutional transformation.

The present article builds on the GreenTeach research findings and provides an analytical overview of the integration of sustainability within VET systems in Bulgaria, Italy, Romania, and Turkey. The analysis combines qualitative and quantitative evidence, with particular focus on teachers' competencies, institutional needs, pedagogical readiness, and professional development challenges associated with sustainability education.

Research Design and Methodological Framework

The study employed a mixed-methods research design that combined desk research, policy analysis, expert interviews, and quantitative surveys. This approach enabled both comparative analysis and triangulation of findings across the participating countries.

The qualitative phase included extensive document analysis involving (GreenTeach Output 2.1, n.d.):

- national educational strategies and VET policy frameworks;
- sustainability-related legislation and curriculum guidelines;
- institutional reports and scientific publications.

To complement the documentary analysis, semi-structured interviews were conducted with 20 VET experts (five per partner country) from governmental institutions, vocational schools, training centres, environmental organisations, and policy-development structures. The interviews explored challenges in integrating sustainability, enhancing institutional preparedness, developing teacher competencies, and aligning with the labour market.

The interviewed experts offered unique perspectives and valuable insights on sustainability education and the integration of green practices within VET programs. Their contributions reflect extensive experience across various fields, including environmental education (covering substantial, methodological, and pedagogical aspects), waste reduction practices, ecological innovation, green business models, environmental impact assessments, renewable energy solutions, circular economy strategies,

climate change adaptation, sustainable resource management, and policy development.

The quantitative phase consisted of an online survey among VET educators based on an online questionnaire structured into six distinct sections to systematically gather investigate:

- teachers' awareness of sustainability frameworks;
- confidence in applying sustainability competencies;
- familiarity with innovative pedagogical methodologies;
- digital competencies;
- professional development needs and preferences.

During this research phase, data and feedback were gathered from 204 VET educators across Bulgaria, Italy, Romania, and Turkey. The combination of qualitative and quantitative evidence enabled the identification of common trends, structural barriers, and country-specific differences concerning the integration of sustainability within VET.

Sustainability Integration as a Systemic Educational Priority

The findings reveal a growing institutional and political recognition of sustainability as a strategic priority within VET systems. Across all participating countries, national reforms increasingly align vocational education with green transition policies and labour-market requirements associated with sustainable development.

The documentary research conducted within the GreenTeach project revealed that VET systems are progressively expected to contribute not only to employability but also to ecological responsibility, resource efficiency, and circular economy practices. This transformation reflects broader European policy objectives that link vocational education to sustainable competitiveness and economic resilience.

Despite strong policy-level commitments, the practical implementation of sustainability in VET remains uneven and often fragmented. One major challenge faced by all the countries taking part in this process is the modernisation of VET curricula with respect to sustainability and the green economy. Efforts to facilitate the easy incorporation of green concepts and sustainability within the framework of vocational education and training are showing some successes but also many challenges. Although there is growing appreciation of the importance of sustainability, the way sustainability education is currently delivered in vocational education and training has certain limitations.

Expert interviews identified several persistent barriers, including:

- outdated curricula;
- insufficient teacher preparation;
- limited institutional resources;
- weak cooperation with industry stakeholders;
- lack of standardised sustainability-oriented teaching frameworks.

Expert interviews and research in Italy revealed that, despite sustainability increasingly being recognised as a strategic priority in VET, this is supported by green transition policies, Agenda 2030 initiatives, and the growing role of environmental organisations in teacher training. However, sustainability education remains fragmented and overly theoretical, with limited practical application, insufficient curricular depth, and a need for a dedicated interdisciplinary framework that can translate student awareness into concrete green skills. The Bulgarian and Romanian reports particularly emphasise the need for stronger continuing professional development systems to support sustainability-oriented teaching practices. Meanwhile, the Turkish analysis highlights systemic difficulties related to curriculum flexibility, stakeholder cooperation, and gaps in educator qualifications.

These findings suggest that sustainability integration within VET should be understood not merely as curriculum reform but as a multidimensional institutional transformation process.

Demographic and Professional Characteristics of VET Educators

The demographic profile of respondents indicates a predominantly mature and highly experienced teaching population. Most participants were in the 35-54 age group, and a substantial proportion reported more than 15 years of professional teaching experience. Specifically, 69% of respondents in Romania and Turkiye, 38% in Italy, and 57% in Bulgaria. The survey also identified a strong predominance of female educators, 71%.

The respondents represented diverse vocational and disciplinary fields, including:

- Education, Humanities, and Inclusion (24.02%);
- Business, Commerce, and Administration (18.63%);
- Science, Technology, ICT, and Engineering (22.05%);
- Manufacturing and Applied Technical Fields (4.41%);
- Health, Social Care, and Agriculture (7.35%);
- Tourism, Sustainability, and Emerging/Interdisciplinary Areas (23.53%).

This diversity confirms that sustainability integration in VET must be treated as a transversal competence applicable across multiple vocational domains rather than as a narrowly environmental subject area.

Awareness of Sustainability Frameworks and Green Standards

One of the central findings concerns teachers' limited familiarity with sustainability frameworks and standards. Although most educators recognised the importance of sustainability in vocational education, their understanding of specific European frameworks remained relatively low (GreenTeach Output 2.2, n.d.).

Only 13.36% of respondents described themselves as "very familiar" with the GreenComp framework, while 38.89% reported being "moderately familiar". By contrast, 23.53% define themselves as "slightly familiar", and 18.55% as "not familiar at all".

Similarly, familiarity with international sustainability standards such as ISO 14001, EMAS, and the Sustainable Development Goals (SDGs) remained limited. Only 12.3% of the respondents indicated high familiarity, 27.4% reported moderate familiarity. A significant number of the educators (24.5%) reported having no familiarity at all.

These data confirm the findings of the European and international standardisation organisations ISO, IEC, CEN and CENELEC, which indicate that standards-based learning remains only marginally integrated into VET systems across Europe. The existing VET provision often lacks structured, competence-based training in sustainability and social responsibility standards and standardisation, contributing to persistent workforce skills mismatches and weakening the innovation and competitiveness of European businesses relative to other regions worldwide (International Federation of Standards Users, 2018; ISO, n.d.; Gabriel, de Vries, & Cleeland, 2022). The results reveal a significant discrepancy between policy expectations and teachers' operational preparedness for sustainability-oriented education. At the same time, the study demonstrates a strong willingness among educators to engage with sustainability topics. Overall, 79.41% of respondents reported integrating sustainability-related themes into their teaching, with 28.91% doing so regularly and 50.50% occasionally.

This indicates that teachers acknowledge sustainability as educationally relevant, even when they lack formal methodological preparation or a comprehensive conceptual understanding.

Pedagogical Readiness and Innovative Teaching Approaches

The transition towards sustainability-oriented education requires significant pedagogical transformation. Traditional teacher-centred instructional

approaches are often insufficient for developing competencies such as systems thinking, critical reflection, collaboration, and problem-solving that are associated with sustainability education (GreenTeach Output 2.2, n.d.).

The survey findings indicate that educators show considerable interest in innovative methodologies, particularly Problem-Based Learning, Inquiry-Based Learning, Experiential Learning, Design Thinking, and Microlearning. Among these methodologies, Project-Based Learning, Inquiry-Based Learning, Experiential Learning, case studies and field-based learning activities were perceived as the most effective for sustainability education (Montes de Oca, Navarro, & Byers , 2026; Al Badawi, 2025).

However, the research also revealed substantial training deficits. In Romania, for example, 88.9% of teachers reported receiving no formal training in these contemporary pedagogical methodologies. Similar patterns emerged across the other participating countries.

Despite these limitations, the willingness to participate in Continuous Professional Development (CPD) was exceptionally high. 96.8% of Bulgarian educators, 97.2% of Romanian educators, 91.7% of Italian educators and 75.8% of Turkish educators involved in the survey declared readiness and commitment to participate in CPD initiatives.

These findings suggest that the principal obstacle to sustainability integration is not resistance among educators but rather insufficient access to structured professional development opportunities.

Digital Competencies and Technology-Enhanced Sustainability Education

The research also examined the relationship between digital preparedness and sustainability education. The findings demonstrate that educators generally recognise the importance of digital technologies in developing sustainability-oriented educational resources and learning environments. Interest in digital training for sustainability education was remarkably high, exceeding 90% across all countries. Specifically, 95% in Bulgaria, 93.9% in Turkiye, and 91.7% in Italy and Romania.

Nevertheless, confidence levels regarding the practical use of digital tools varied considerably between countries. Romanian teachers demonstrated comparatively higher confidence, with 75% reporting that they use digital technologies effectively or very effectively. In Italy, however, 20.83% reported low confidence levels regarding the development of digital educational resources.

These disparities highlight the interconnected nature of the green and digital transitions. Sustainability education increasingly requires

competencies not only in environmental awareness but also in digital literacy, online collaboration, simulation technologies, and technology-enhanced learning environments.

Professional Development Needs and Institutional Perspectives

The study consistently identifies Continuing Professional Development (CPD) as one of the most critical prerequisites for effective sustainability integration within VET systems.

Teachers expressed strong preferences for flexible, practice-oriented training models. Blended learning formats were particularly preferred by 52.4% of Bulgarian respondents, 52.8% of Romanian respondents and 43.1% of Italian VET educators involved in the survey.

Online courses were also highly valued by 50.8% of Bulgarian and 41.7% of Italian respondents.

In contrast, Turkish respondents demonstrated a stronger preference for face-to-face workshops (66.7%).

The main priorities for future professional development identified in the survey include:

- stronger cooperation with industry stakeholders;
- curricular integration of sustainability;
- digital tool implementation;
- understanding and application of GreenComp competencies.

This study therefore proves the necessity of significant investment in institutional development to build teachers' capacities. In line with GreenTeach, curriculum change alone will not guarantee successful integration, because success also requires changing the attitudes and perceptions of both teachers and learners.

Conclusion

The findings of the GreenTeach research provide substantial evidence that integrating sustainability into VET systems has become an educational and socioeconomic necessity. Across Bulgaria, Italy, Romania, and Turkey, VET educators increasingly recognise the importance of sustainability competencies for future workforce development and social resilience.

At the same time, the research highlights a persistent gap between institutional ambitions and operational preparedness. Teachers demonstrate high levels of motivation and willingness to engage with sustainability education, yet many lack familiarity with sustainability frameworks and

modern technology-enhanced educational approaches, relevant digital competencies and access to structured professional development.

The results also demonstrate that integrating sustainability cannot be reduced to isolated curricular modifications. Instead, it requires systemic institutional transformation involving strategic leadership, industry collaboration, pedagogical innovation, investment in teacher competencies, and finally, long-term policy support.

Ultimately, strengthening teachers' sustainability competencies is a fundamental systems prerequisite for developing greener, more inclusive, and future-oriented vocational education that can respond effectively to the ecological and technological challenges of contemporary society.

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References:

1. Al Badawi, H. (2025, pp. 593-626). IGI Global Scientific Publishing.). Transformative Educational Strategies for Global Sustainability Literacy. In M. Mokdad (Ed.). Retrieved from Social System Reforms to Achieve Global Sustainability: https://doi.org/10.4018/979-8-3373-1280-4.ch021
2. CEDEFOP. (2020). Osnabrück Declaration on VET. Retrieved from https://www.cedefop.europa.eu/files/osnabrueck_declaration_eu2020.pdf
3. European Commission. (2022). GreenComp: the European sustainability competence framework. Retrieved from GreenComp: the European sustainability competence framework: https://joint-research-centre.ec.europa.eu/greencomp-european-sustainability-competence-framework_en
4. European Union. (2020, Nov). Council Recommendation of 24 November 2020 on vocational education and training (VET) for sustainable competitiveness, social fairness and resilience. Retrieved from CEDEFOP: https://www.cedefop.europa.eu/en/content/council-recommendation-24-november-2020-vocational-education-and-training-vet-sustainable

5. Gabriel, L., de Vries, H., & Cleeland, B. (2022). Stimulating Education about Standardization – Activities and perspectives of National Standards Bodies. Retrieved from Journal of Standardisation Vol. 1,: file:///C:/Users/Mariya/Downloads/fgrillo,+6298+Article+Stimulating+Education+about+Standardization.pdf
6. GreenTeach Output 2.1. (n.d.). DEV 2.1 Current State of the Integration of Green and Sustainability Competencies in VET. Retrieved from https://greenteach.eu-track.eu/greenteach/upload/web_comp/add/doc/000000190_1747128251.pdf
7. GreenTeach Output 2.2. (n.d.). DEV 2.2 Environmental Protection and Green Economy Shifting Teachers' Competencies Report. Retrieved from https://greenteach.eu-track.eu/greenteach/upload/web_comp/add/doc/000000213_1746019884.pdf
8. GreenTeach. (n.d.). TRANSFORMING TEACHING FOR A GREENER PLANET. Retrieved from https://greenteach.eu/
9. International Federation of Standards Users. (2018). IFAN Publications. Retrieved from Guide 4:2018 Education and Training about Standardization (Updated 2018 and corrected by corrigenda 1): https://www.ifan.org/Final_Paris_IFAN%20Guide%204_V1.pdf
10. ISO. (n.d.). ISO - Strategy 2030. Retrieved from https://www.iso.org/strategy2030.html
11. Montes de Oca, L., Navarro, M., & Byers, T. (2026). Understanding what makes sustainability education effective: Insights from a university certificate program. Retrieved from Cleaner Production Letters (CLPL): https://doi.org/10.1016/j.clpl.2026.100133

PHD STUDENT SESSION

AN OPEN MODULAR ARCHITECTURE FOR SUSTAINABLE MARITIME DIGITAL TWINS

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Abstract: *Proprietary maritime digital twins create vendor lock-in that outlasts multi-decade vessel lifecycles. This paper proposes a modular, open architecture to maximize digital twin longevity. Utilizing open-source standards for telemetry, simulation, and visualization, this framework aligns digital infrastructure with circular economy principles, eliminating software obsolescence.*

Keywords: *maritime digital twins, sustainability, modular architecture, open-source systems, circular economy, IoT, edge computing, maritime informatics*

1. INTRODUCTION

Digital twins are increasingly vital in maritime operations, integrating operational data streams from engines, navigation, cargo, weather, and environmental systems into virtual models supporting real-time decision-making. However, commercial adoption is hindered by proprietary cloud ecosystems and closed software stacks, causing structural issues:

- **Limited interoperability between heterogeneous marine systems.**
- **Heavy reliance on single software vendors.**
- **High-friction, expensive platform migration paths.**
- **Siloed or restricted access to historical operational data.**
- **Escalating long-term maintenance and licensing fees.**

These constraints are acute in maritime environments because vessels operate for 25–30 years—far outlasting the commercial lifecycle of proprietary software. Vendor deprecation leads to premature infrastructure obsolescence, demonstrating a linear "take-make-dispose" engineering model. To achieve circular sustainability, shipping software must mirror physical asset longevity. This paper proposes an open, modular architectural philosophy built from interchangeable components instead of monolithic systems. The framework relies on three technical pillars:

- **Simplicity:** Minimizing abstraction layers to optimize maintenance overhead.
- **Modularity:** Isolating components to allow independent upgrades over a 30-year lifecycle.
- **Interoperability:** Employing open data standards to eliminate data lock-in.

2. RESEARCH METHODOLOGY

This study applies design science research methodology to develop a conceptual architecture for sustainable maritime digital twins. The systematic design process involved:

Analyzing leading industrial digital twin frameworks, focusing on lifecycle data management. Comparing proprietary and open-source software platform lifecycles. Evaluating maritime communication constraints, specifically satellite bandwidth limits. Examining edge-to-cloud operational synchronization dependencies. Synthesizing modular architectural principles from distributed systems engineering.

Adhering to a strict "keep it simple" approach, this framework rejects specialized, tightly coupled dependencies in favor of mature, standard-based, and operationally practical technologies. The architecture was conceptually validated against primary maritime scenarios: vessel telemetry monitoring, port coordination, route optimization, and environmental simulation.

3. RELATED WORK

The industrial landscape of digital twins has been comprehensively mapped by Tao et al. (2019) in a major state-of-the-art review. Their work highlights that digital twins rely on the seamless integration between cyber and physical spaces, with successful applications across product design, production, and health management. While Tao et al. (2019) outline the core components and open challenges for general industry, this paper expands on those foundations by focusing specifically on the architectural sustainability and long-term lifecycles required for maritime operations.

4. ARCHITECTURAL PHILOSOPHY: KEEP IT SIMPLE

The proposed architecture is governed by a singular rule:

"Every layer should be replaceable without redesigning the entire system." This approach fuses modular systems engineering with Clean Architecture principles, decoupling concerns into independent layers via open standards rather than code dependencies. This ensures multi-decade operational agility:

- Replacing visualization tools without altering underlying telemetry pipelines.
- Upgrading simulation engines without changing the core data streaming backbone.
- Migrating cloud infrastructure providers without risking historical data loss.
- Modernizing localized infrastructure has been incrementally over decades.

This decoupling directly prevents digital obsolescence, preserving the digital twin as a functional operational asset for the vessel's full lifecycle.

5. HIGH-LEVEL ARCHITECTURE

Table 1 maps the framework's five independent, interoperable layers.

ARCHITECTURAL LAYER	PRIMARY ROLE	CORE TECHNOLOGIES	SUSTAINABILITY & INTEROPERABILITY CONTRIBUTION
5. Visualization & Decision Layer	Human interaction, monitoring, and operational decision support	QGIS, OpenCPN	Provides open geospatial visualization without dependence on proprietary navigation or GIS ecosystems.
4. Simulation & Analytics Layer	Predictive analytics and environmental simulation	OpenFOAM, MITgcm, ROMs, Surrogate Models	Enables computationally efficient optimization, fuel reduction, and extended operational asset efficiency.
3. Data Streaming Layer	Distributed asynchronous event communication	Apache Kafka	Decouples system components and supports scalable long-term infrastructure evolution.
2. Context & Digital Twin Layer	Digital asset state management and semantic contextualization	Eclipse Ditto, FIWARE, NGSI-LD	Maintains interoperable digital representations across vessels, ports, and logistics systems.
1. Asset & Edge Device Layer	Telemetry acquisition, preprocessing, and edge communication	Sensors, AIS, MQTT 5.0, Edge Processing	Reduces bandwidth consumption and supports resilient maritime edge-to-cloud operations.

6. ASSET AND EDGE DEVICE LAYER

The foundational layer comprises physical maritime components (propulsion, auxiliary engines, ballast, AIS, navigation, and weather sensors). Because maritime operations suffer from satellite bandwidth constraints and intermittent sea connectivity, continuous transmission of raw telemetry is impractical. The edge layer applies to lightweight preprocessing algorithms before transmission:

- **Down sampling:** Reducing data transmission frequency during steady operational states.
- **Dead banding:** Transmitting data points only when they breach predefined thresholds.
- **Local aggregation:** Compiling high-frequency bursts into statistical averages.
- **Compression:** Optimizing telemetry payload packages for satellite transfer.

Consequently, only high-value, processed telemetry is streamed via MQTT 5.0, minimizing costly bandwidth while preserving real-time visibility.

7. CONTEXT AND DIGITAL TWIN LAYER

Raw data streams require operational context. This layer structures relationships between virtual models and their physical maritime environments.

7.1 Eclipse Ditto for Vessel Twins

Eclipse Ditto maintains the operational state of maritime assets. Each vessel is a structured digital object tracking static metadata (dimensions, capacities) and dynamic telemetry (RPM, fuel metrics). Ditto manages persistent digital shadowing, allowing shore-based analytical logic to run uninterrupted during temporary satellite dropouts.

7.2 FIWARE and NGSI-LD for Context Modeling

Port environments require broader context. FIWARE and the NGSI-LD standard model real-time semantic relationships between vessels, berths, cranes, weather stations, and supply chains. This linked-data architecture facilitates standardized asset-to-port coordination.

8. DATA STREAMING LAYER

Apache Kafka serves as the central event-streaming backbone, decoupling data producers from consumers. Onboard sensors, simulation engines, and dashboards communicate asynchronously. This decoupling ensures that adding new analytics services or third-party logistics tools requires zero modification to the core telemetry infrastructure, facilitating scalability and structural resilience.

9. SIMULATION AND ANALYTICS LAYER

Real-time operational pipelines cannot directly run computationally intensive hydrodynamic or oceanographic simulations. To resolve this, the layer uses Reduced-Order Models (ROMs) and machine learning surrogate models trained offline. Heavy simulations are run offline using OpenFOAM (for hull resistance/CFD) and MITgcm (for regional ocean circulation). The resulting datasets train lightweight neural networks or Gaussian Process Regression models. These surrogates execute near-instantaneously within the active digital twin pipeline to provide real-time insights regarding trim optimization, fuel efficiency, weather routing, and predictive maintenance, enhancing asset longevity.

10. VISUALIZATION AND DECISION SUPPORT

This layer converts analytical data into actionable human interfaces.

10.1 QGIS

Powers shore-based geospatial analytics, allowing operators to monitor fleet trajectories, port congestion, and environmental conditions.

10.2 OpenCPN

Provides lightweight, onboard open-source navigation overlays and weather-routing displays. Both platforms employ open charting standards, eliminating reliance on proprietary GIS software.

11. INTEROPERABILITY STANDARDS AND SECURITY

The architecture relies strictly on a curated selection of open standards to minimize lock-in, outlined in Table 2.

Table 2. Key open standards and protocol applications across the framework.

STANDARD / PROTOCOL	ARCHITECTURAL PURPOSE	SUSTAINABILITY & INTEROPERABILITY CONTRIBUTION
MQTT 5.0	Lightweight telemetry transport from edge to cloud.	Minimize satellite bandwidth overhead and prevent edge-to-cloud data loss under weak connections.
NGSI-LD	Contextual semantic modeling and relationship linking.	Enables standardized asset-to-port communication using linked data principles.
Kafka Events	Distributed asynchronous streaming backbone.	Decouples ingestion from consumption layers, ensuring independent multi-decade infrastructure lifecycles.
NetCDF	Standardized scientific and environmental data exchange.	Formats multi-dimensional simulation data matrices without proprietary vendor software dependencies.

Cybersecurity governance is embedded directly into the streaming framework using distributed role-based access control (RBAC), mutual TLS (mTLS) encryption, and cryptographically signed data envelopes.

12. ADVANTAGES OF THE PROPOSED ARCHITECTURE

The framework delivers clear operational benefits over monolithic software suites:

- **Minimal Vendor Dependency:** Full control over data infrastructure and migration options.
- **Long-Term Sustainability:** Digital assets evolve systematically along with 30-year vessel lifecycles.
- **High Flexibility:** Independent layer updates prevent system-wide software breaking points.
- **Reduced Overhead:** Lowers licensing costs by prioritizing enterprise open-source technology.
- **Enhanced Ecosystem Integration:** Open API standards unify communication between ships, smart ports, and logistics systems.

13. LIMITATIONS

Modular open architectures demand mature organizational DevOps capabilities, skilled systems integration engineers, and complex distributed infrastructure management. Additionally, this architecture is tuned for operational analytics and scheduling rather than low-latency control loops; safety-critical automation must remain physically isolated within onboard industrial control systems.

14. CONCLUSION

This paper demonstrates that sustainable maritime digital twins do not require monolithic proprietary software. Long-term lifecycle extension is achievable through a modular architecture based on open data standards, loose component coupling, and systemic simplicity.

By combining edge preprocessing, event streaming, context models, lightweight simulation surrogates, and open-source visualization, the proposed framework establishes a scalable, maintainable, and circular digital infrastructure for shipping. Future work will investigate prototype validation, network latency benchmarking, and real-world smart port deployments.

References:

1. Apache Software Foundation. (2024). Apache Kafka Documentation. https://kafka.apache.org/documentation/
2. Eclipse Foundation. (2024). Eclipse Ditto Documentation. https://www.eclipse.org/ditto/

3. FIWARE Foundation. (2024). FIWARE NGSI-LD Specification. https://www.fiware.org/
4. MITgcm Group. (2024). MIT General Circulation Model Documentation. http://mitgcm.org/public/r2_manual/latest/
5. OpenCPN Development Team. (2024). OpenCPN User Manual. https://opencpn.org/
6. OpenFOAM Foundation. (2024). OpenFOAM User Guide. https://openfoam.org/doc/
7. QGIS Development Team. (2024). QGIS Documentation. https://qgis.org/
8. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415.

ПОКОЛЕНИЕ Z МЕЖДУ НЕЗАБАВНОТО И ОТЛОЖЕНОТО УДОВЛЕТВОРЕНИЕ В ДИГИТАЛНАТА СРЕДА: ПРЕДИЗВИКАТЕЛСТВА ПРЕД РАБОТОДАТЕЛСКАТА МАРКА

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GENERATION Z BETWEEN IMMEDIATE AND DELAYED GRATIFICATION IN THE DIGITAL ENVIRONMENT: CHALLENGES FOR EMPLOYER BRANDING

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Abstract: *The paper examines the influence of the culture of immediacy on Generation Z career attitudes and its implications for employer branding. The study aims to analyze the relationship between immediate and delayed gratification, feedback expectations, and trust in the employer. It builds on the concept of delayed gratification (Marshmallow Test) and an empirical survey among 102 students from Paisii Hilendarski University of Plovdiv. The findings highlight immediate feedback and trust as key factors for long-term engagement and suggest the need to adapt organizational practices through staged structuring of progress and future benefits.*

Keywords: *Generation Z, immediate gratification, delayed gratification, employer branding, feedback*

Въведение

Дигиталната среда трансформира не само начина, по който младите хора комуникират, учат и вземат решения, но и начина, по който възприемат труда, развитието и организационните отношения. Поколение Z, като първото поколение, израснало изцяло в условията на постоянна свързаност и ускорен достъп до

информация, често се свързва с култура на незабавно удовлетворение, кратки цикли на внимание и очакване за бърз отклик. Тези характеристики поставят нови въпроси пред организациите и работодателската марка. Ако традиционните модели на кариерно развитие предполагат търпение, отложени ползи и постепенно израстване, то възниква въпросът доколко тези модели остават валидни за поколение Z и как работодателите могат да адаптират своите практики към новите очаквания.

Класическата концепция за отложеното удовлетворение, позната чрез Marshmallow Test, предлага полезна теоретична рамка за подобен анализ. В условията на дигитална среда обаче тя изисква нов прочит, тъй като дългосрочните ползи често се оценяват през призмата на видим прогрес, незабавна обратна връзка и краткосрочни сигнали за развитие. В този контекст настоящото изследване разглежда връзката между нагласите към незабавно и отложено удовлетворение, очакванията за обратна връзка и възприемането на работодателската марка. Специален фокус се поставя върху въпроса дали предизвикателството е в липсата на готовност за дългосрочен ангажимент, или в начина, по който организациите комуникират и структурират бъдещите ползи. Целта на доклада е, чрез емпирично изследване сред студенти от поколение Z, да се анализират тези зависимости и да се очертаят възможни насоки за адаптация на employer branding практиките.

Теоретична рамка

Концепцията за отложеното удовлетворение традиционно се свързва със способността индивидът да отложи непосредствена награда в полза на по-голяма бъдеща полза. Класическият Marshmallow Test поставя основите на тази перспектива и демонстрира връзката между самоконтрола и дългосрочните поведенчески резултати (Mischel et al., 1989). По-късни изследвания показват, че склонността към отложено удовлетворение не е само индивидуална характеристика, а зависи и от контекста и доверието в средата (Kidd et al., 2013). В контекста на дигиталната среда този модел изисква преосмисляне. Постоянният достъп до информация, алгоритмично стимулирана незабавност и ускорените цикли на обратна връзка променят не непременно готовността за дългосрочна ориентация, а начина, по който тя се възприема и поддържа. Поколение Z, като първото

поколение, израснало изцяло в дигитална среда, се характеризира с високи очаквания за бърз отклик, прозрачност и видим прогрес (Deloitte, 2023; Twenge, 2017). Част от изследванията свързват тези особености с по-силна ориентация към краткосрочни стимули, докато други подчертават значението на вътрешната мотивация, смисъла и възможностите за развитие като ключови фактори за ангажираност (Ryan & Deci, 2000; Schaufeli, 2013). Това предполага, че предизвикателството не е в отсъствието на дългосрочна ориентация, а в начина, по който тя се преживява от индивида. От тази перспектива работодателската марка не се разглежда само като инструмент за привличане на таланти, а като механизъм за формиране на очаквания и възприятия за развитие (Backhaus & Tikoo, 2004; Mosley, 2014). Особено значение придобиват комуникацията на бъдещи ползи, сигналите за прогрес и регулярната обратна връзка като фактори, които могат да направят дългосрочните перспективи психологически по-близки и постижими. В този смисъл настоящото изследване стъпва върху разбирането, че предизвикателството може да не е в самото отложено удовлетворение , а в начина, по който организациите го „архитектират“ чрез микро-сигнали за напредък, доверие и поетапно развитие. Това разбиране поставя основа за търсене на модели, които свързват краткосрочните сигнали за прогрес с дългосрочната организационна ангажираност. В този контекст може да се направи разграничение между класическото разбиране за отложено удовлетворение като индивидуална способност и неговото съвременно проявление като процес, силно зависим от средата. Дигиталната среда и организационните практики създават условия, при които очакванията за бърз отклик и видим прогрес не изключват дългосрочна ориентация, а я трансформират. Това предполага, че способността за отложено удовлетворение при поколение Z не следва да се разглежда като стабилна личностна характеристика, а като динамична функция на контекста, в който се осъществява.

Методология

Изследването е проведено чрез анкетно проучване сред 102 студенти от Пловдивския университет „Паисий Хилендарски“. Извадката включва участници с различен образователен и трудов статус, което позволява анализ на нагласи, свързани с професионално развитие, обратна връзка и възприятия за

работодателската среда. Изследователският инструмент е авторски въпросник, включващ общо 11 твърдения, измерени чрез петстепенна Likert скала (1 - напълно несъгласен до 5 - напълно съгласен). Твърденията са групирани в три основни тематични области: ориентация към незабавно и отложено удовлетворение, очаквания за обратна връзка и възприемане на работодателската марка. Променливите са кодирани както следва: DG (delayed gratification), IG (immediate gratification), FB (feedback), DIG (digital orientation), TRUST (organizational trust) и EB (employer brand perception). Формулирани са следните изследователски хипотези:

1. **X1.** Ориентацията към незабавна обратна връзка и дигитална динамика е положително свързана с очакванията на поколение Z за бързи сигнали за прогрес.
2. **X2.** Доверието към организацията и възприемането на работодателската марка формират самостоятелен фактор, свързан с дългосрочна организационна ангажираност.
3. **X3.** Структурирани микро-сигнали за прогрес могат да подпомагат възприемането на бъдещите ползи в организационен контекст.

Данните са обработени чрез дескриптивен анализ, корелационен анализ и експлораторен факторен анализ (EFA), използвайки JASP. За идентифициране на латентни структури е приложен факторен анализ с oblique rotation (promax), а броят фактори е определен чрез parallel analysis. Резултатите от факторния анализ показват задоволителни стойности на показателите за пригодност на данните (KMO и Bartlett's test), което потвърждава приложимостта на метода за изследване на латентните конструкти.

Таблица 1. Описателни показатели и факторни натоварвания.

Променлива	M	SD	Factor 1	Factor 2
DG1	4.62	0.60		
DG2	4.36	0.75		
IG1	2.91	1.05	0.56	
IG2	2.75	1.10	0.41	
FB1	4.55	0.69	0.68	
DIG1	3.75	0.99	0.41	
DIG2	3.29	1.08		
TRUST1	4.03	0.84		0.64
EB1	4.26	0.77		0.55
TRUST2	4.27	0.76		0.44
EB2	4.25	0.81		

EFA with promax rotation, loadings < 0.30 suppressed.

Бележка:

M - mean (средна стойност)
SD - standard deviation (стандартно отклонение)
Factor 1 - orientation toward immediate feedback and perceived progress (ориентация към незабавна обратна връзка и прогрес)
Factor 2 - trust and employer brand perception (доверие и възприятие за работодателската марка)
DG - delayed gratification (отложено удовлетворение)
IG - immediate gratification (незабавно удовлетворение)
FB - feedback (обратна връзка)
DIG - digital orientation (дигитална ориентация)
TRUST - organizational trust (организационно доверие)
EB - employer brand perception (възприятие за работодателската марка)

Резултати

Дескриптивният анализ показва високи средни стойности по показатели, свързани с доверие, обратна връзка и възприемане на работодателската марка, докато ориентацията към незабавни материални ползи отчита сравнително по-ниски стойности. Това поставя под въпрос еднозначното свързване на поколение Z с доминираща ориентация към незабавно удовлетворение. Корелационният анализ показва, че очакванията за незабавна обратна връзка заемат централно място сред изследваните зависимости и се свързват както с ориентацията към незабавност, така и с дигиталната динамика.

Важно е да се отбележи, че най-високи факторни натоварвания се наблюдават при показателите, свързани с обратна връзка, което подчертава нейната централна роля в структурата на нагласите. Това допълнително подкрепя тезата, че незабавната обратна връзка функционира като ключов механизъм за свързване на краткосрочните очаквания с дългосрочната ангажираност.

Експлораторният факторен анализ идентифицира двуфакторна структура (Таблица 1). Първият фактор обединява елементи, свързани с незабавна обратна връзка, дигитална ориентация и краткосрочни сигнали за прогрес, докато вторият фактор включва доверие и възприемане на работодателската марка. Показателите, свързани с класическото отложено удовлетворение, не формират самостоятелен устойчив фактор. Въз основа на получените резултати може да се обобщи, че Х1 се потвърждава, тъй като незабавната обратна връзка се проявява като централен елемент в установената факторна структура. Х2 се потвърждава, като доверието и възприемането на работодателската марка формират

самостоятелен фактор, свързан с дългосрочната ангажираност. Хз получава частична подкрепа, тъй като резултатите показват, че структурирани сигнали за прогрес имат значение, но не чрез класическия модел на отложено удовлетворение, а чрез механизма на микрообратна връзка.

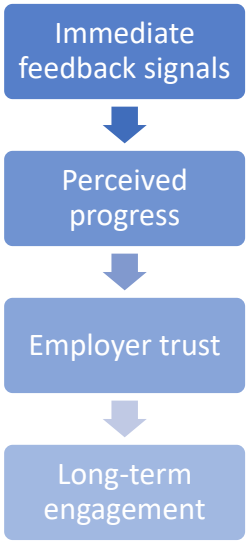
Обсъждане

Резултатите поставят под въпрос опростеното разбиране, че поколение Z се характеризира предимно с ориентация към незабавно удовлетворение. Получените данни показват по-сложна картина, в която очакванията за бърза обратна връзка и видим прогрес изглеждат по-съществени от самото търсене на незабавни награди. Особено значим е фактът, че незабавната обратна връзка се очертава като централен елемент в установената факторна структура. Това насочва към интерпретация, според която ангажираността на поколение Z не се поддържа толкова чрез обещание за далечни бъдещи ползи, колкото чрез поетапни сигнали за развитие, признание и напредък. В този контекст работодателската марка може да се разглежда не само като средство за привличане, а като механизъм за структуриране на възприемания прогрес. Практическо проявление на подобна логика може да се открие в подходи, при които кариерното развитие се представя като последователност от достижими етапи - например преход от входна позиция към по-голяма автономност или предприемаческа роля - вместо като абстрактна дългосрочна перспектива. Тази логика е синтезирана в предложения модел на структурираното удовлетворение (Фигура 1), според който микрообратната връзка, сигналите за прогрес и доверието към работодателя функционират като медиатори между краткосрочните очаквания и дългосрочната ангажираност.

Моделът предполага, че предизвикателството пред работодателите не е дали поколение Z приема отложени ползи, а как тези ползи се проектират и комуникират като постижим прогрес. Подобна логика се потвърждава и в практически контекст, при който кариерното развитие се комуникира не като отдалечена перспектива, а като последователност от ясно дефинирани и достижими етапи. Например при позиции от входно ниво, съчетани с перспектива за преминаване към по-голяма автономност или самостоятелна дейност, се наблюдава повишен интерес от страна на млади кандидати, когато дългосрочната цел

е „раздробена“ на конкретни стъпки с видими критерии за напредък. Това подсказва, че не самата дългосрочна перспектива е проблематична, а липсата на междинни сигнали, които да я направят възприемана като реалистична и постижима.

В този смисъл въпросът не е дали поколение Z приема отложено удовлетворение, а как организациите го правят видимо и постижимо.



Фигура 1. Модел на структурираното удовлетворение (Structured Gratification Model)

Ограничения на изследването

Настоящото изследване има пилотен характер и се основава на извадка от студенти, което ограничава възможностите за генерализация на резултатите. Допълнително, използването на самооценъчни данни създава риск от субективност в отговорите. Бъдещи изследвания биха могли да разширят анализа чрез включване на реални организационни контексти и различни възрастови групи.

Заключение

Настоящото изследване разглежда връзката между нагласите на поколение Z към незабавно и отложено удовлетворение и предизвикателствата пред работодателската марка в дигитална среда. Резултатите не потвърждават еднозначно разбирането, че

поколение Z е доминиращо ориентирано към незабавни награди, а по-скоро очертават значението на незабавната обратна връзка, сигналите за прогрес и доверието към организацията. Емпиричните данни показват, че ангажираността на младите хора може да се подкрепя не толкова чрез обещание за отложени ползи само по себе си, а чрез поетапно структуриране на развитието и комуникиране на бъдещите възможности като видим и достижим прогрес. Основният принос на изследването се състои в извеждането на модел на структурираното удовлетворение, който предлага нов прочит на връзката между краткосрочните очаквания и дългосрочната ангажираност. От практическа гледна точка резултатите насочват към необходимост employer branding практиките да се адаптират чрез модели, които комбинират микрообратна връзка, доверие и последователни сигнали за развитие.

Изследването има пилотен характер и предполага бъдещо разширяване чрез по-големи извадки и различни организационни контексти.

Литература:

1. Backhaus, K., & Tikoo, S. (2004). Conceptualizing and researching employer branding. Career Development International, 9(5), 501-517. https://doi.org/10.1108/13620430410550754
2. Cable, D. M., & Turban, D. B. (2001). Establishing the dimensions, sources, and value of job seekers' employer knowledge. Research in Personnel and Human Resources Management, 20, 115-163.
3. Deloitte. (2023). 2023 Global Gen Z and Millennial Survey. Deloitte Insights. https://www.deloitte.com/global/en/about/press-room/2023-gen-z-and-millenial-survey.html
4. Kaplan, A. M., & Haenlein, M. (2010). Users of the world, unite! The challenges and opportunities of social media. Business Horizons, 53(1), 59-68. https://doi.org/10.1016/j.bushor.2009.09.003
5. Kidd, C., Palmeri, H., & Aslin, R. N. (2013). Rational snacking: young children's decision-making on the marshmallow task is moderated by beliefs about environmental reliability. Cognition, 126(1), 109-114. https://doi.org/10.1016/j.cognition.2012.08.004
6. Mischel, W., Shoda, Y., & Rodriguez, M. L. (1989). Delay of gratification in children. Science, 244(4907), 933-938. https://doi.org/10.1126/science.2658056

7. Mosley, R. (2014). Employer brand management: Practical lessons from the world's leading employers. Wiley.
8. Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. Contemporary Educational Psychology, 25(1), 54-67. https://doi.org/10.1006/ceps.1999.1020
9. Schaufeli, W. B. (2013). What is engagement? In C. Truss et al. (Eds.), Employee engagement in theory and practice (pp. 15-35). Routledge.
10. Twenge, J. M. (2017). iGen: Why today's super-connected kids are growing up less rebellious, more tolerant, less happy-and completely unprepared for adulthood. Atria Books.

THE DIGITAL TWIN IN BORDER SECURITY AT EUROPEAN UNION AIRPORTS: SYNERGY BETWEEN ADVANCE DATA ANALYSIS AND AUTOMATED BIOMETRIC SYSTEMS

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Abstract: *The paper examines the "digital twin" concept in contemporary border security at EU international airports through the synergy between advance passenger data analysis systems and automated biometric control. Emphasis is placed on the interoperability of information systems and their integration into the Common Data Repository, through which proactive risk analysis is achieved. Challenges and trends in border security are outlined.*

Keywords: *border security, biometric control, interoperability, risk analysis, artificial intelligence*

I. INTRODUCTION

To address contemporary challenges, European Union's (EU) border security systems have leveraged a concept originally developed in the engineering sciences, which holds the potential to vastly improve EU border security—the "digital twin" concept. Although this specific term is not used in academic and legal circles related to EU border security, in the reality of airport border security, this concept acquires strategic significance. For the purposes of border security, the concept features a detailed, real-time updated virtual profile of the passenger, created through the precise aggregation of data via information systems. This virtual profile is not in a static state; rather, it is continuously updated through the interoperability of various information systems. According to European legislation, the passenger's "digital twin" contains information regarding: biographical data, biometric data, reservation data, and more. All of these are updated in real time, turning the passenger's profile into a dynamic "digital twin".

The main objective of this paper is to examine the significance and integration of the "digital twin" concept through the prism of border security at EU international airports. The scope of the study focuses on the implementation in the EU of the following systems:

- advance information – the European Travel Information and Authorisation System (ETIAS) and the systems for processing Advance Passenger Information (API) and Passenger Name Record (PNR) data;

- automated airport biometrics – Automated Border Control (ABC) systems (or e-gates) and the Entry/Exit System (EES).

Through analysis, synthesis, deduction, induction, a systemic approach, comparison, and conceptual modeling, the paper aims to demonstrate how the interoperability of information databases can transform border control from a reactive physical barrier into a proactive method for border security.

II. ADVANCE DATA ANALYSIS: FORMING THE DIGITAL PROFILE PRIOR TO ACTUAL TRAVEL

The traditional model of border control, in which the passenger check begins only at the moment of their physical appearance in front of the border guard at the Border Crossing Point (BCP), is no longer capable of effectively responding to the passenger volume and the specificities of modern air traffic. At the same time, the EU has bilateral agreements with numerous countries that guarantee visa-free travel for EU citizens and the citizens of the respective countries across each other's borders. For the EU, revoking such agreements means restricting the acquired rights of EU citizens and a blow to its prestige. Therefore, in response to current migration threats, the EU is gradually shifting toward a security architecture that projects the border virtually outside the physical territory of the EU Member States. This preliminary filtration process is carried out through integrated systems for advance information and data analysis. These systems generate the initial dataset necessary to construct the passenger's "digital twin", and this takes place before the actual travel is realized.

A foundational element in this new architecture is the ETIAS system, which is implemented through two EU legal acts. The first[1] formulates the legal framework of the new system, while the second[2] amends existing provisions in other European legal acts so that EU law enforcement institutions (Europol, Eurojust, etc.) have access to the system. The operational goal of ETIAS is to act as a preliminary sieve for third-country nationals who are exempt from visa requirements under EU law. Prior to the implementation of this mechanism, this category of passengers arrived at European airports without a preliminary check regarding their fulfillment of entry requirements, particularly concerning checks against Interpol databases, the Schengen Information System (SIS), and national databases. This constituted a significant vulnerability in the border security system. Through ETIAS, every individual (which is subject to registration in the

system) is required to declare their biographical data and travel intentions in advance. The system automatically cross-checks the inputted information in EU security databases. This allows competent authorities to identify potential risks related to terrorism, serious crime, illegal migration, and others. In the context of the examined concept, ETIAS creates the first layer of the "digital twin"—a basic biographical profile that answers the question of whether the individual has the right to initiate their travel to the EU borders. Additionally, issuing an ETIAS travel authorization brings a financial benefit to the EU, as the authorization requires a specific, albeit minimal, fee paid by the applicant.

While ETIAS covers a strictly specific group of passengers, API and PNR add the next, significantly more detailed layer to the virtual profile of every passenger, regardless of their nationality. The strength of these two instruments lies in the complementarity between the two types of data. While API data provide confirmed, static information (names, nationality, passport number, date of birth, etc.), PNR data reveal the behavioral model of the individual. PNR data are dynamic and contain details about the entire routing, payment method, the travel agency that issued the ticket, contact details, baggage volume, and the presence of co-travelers. Driven by the requirement to achieve full interoperability between systems, the EU recently adopted two regulations[3][4] that updated the EU provisions on API data to achieve interoperability and harmonized handling of the massive volume of information. Meanwhile, the PNR directive[5] remained unchanged, as it currently meets the interoperability requirements between EU systems. It should be noted that under European and national legislation, every air carrier is obliged to provide API data to the Member States' national units, as well as information for creating a PNR profile (IP address and other digital information that can link the passenger to the characteristics of another passenger).

According to European legislation, the analysis of this massive dataset is administered by the Passenger Information Units (PIUs) (in Bulgaria, the National Unit for Receiving and Processing Passenger Reservation Data within the State Agency "National Security"), which in practice function as specialized analytical centers. There, utilizing specialized software algorithms, this aggregation of data is processed to filter passengers even before a flight to the EU departs. The analysis process operates in two main directions: screening against known threats (cross-checking against information entered in SIS, Interpol, and national databases) and analyzing unknown risks. The second direction (analysis of unknown risks) is of critical importance, as it is precisely through this that algorithms can apply pre-set

risk criteria to detect anomalies. This enables the construction of behavioral profiles corresponding to the tactics used by organized crime groups or human trafficking and illegal migration networks.

Interim conclusion: The joint functioning of the ETIAS system and the API/PNR datasets builds one half of the comprehensive "digital twin" concept—its biographical and behavioral essence. When the flight takes place and the passenger steps onto the territory of an EU international airport, national authorities no longer act reactively; they possess a pre-constructed virtual identity that has undergone precise preliminary risk analysis. This provides the necessary technological time for security services to target high-risk profiles and informs border control services while ensuring the unhindered and faster border crossing of legitimate travelers. Furthermore, if there is an attempt to conceal joint travel through separate bookings, the national units have the capability to perform network analysis. By matching hidden indicators such as a shared IP address, identical payment methods, or linked contact data, the system can automatically link passengers into organized groups, which aids the construction of the "digital twin's" behavioral model.

III. AUTOMATED BORDER CONTROL: BIOMETRIC VERIFICATION AT THE AIRPORT

As previously noted, the first half of forming the "digital twin" is completed prior to the commencement of the individual's travel. However, although the profile is detailed, it is still incomplete, and several risks of circumventing the border regime remain. This is exactly why the second half of constructing the "digital twin" is necessary. It begins upon the passenger's arrival at an EU international airport and consists of their physical and biometric verification on-site. This phase is characterized by the joint operation of ABC (Automated Border Control) (or e-gates) systems and the EES (Entry/Exit System). In this second stage, the digital model built during the first stage is cross-referenced with the real physical subject through ABC and EES, thereby ensuring high-precision identification in real time.

The operational deployment of ABC in EU border control is a strictly formulated process, carried out on the basis of Regulation (EU) 2017/2225[6], which amended the Schengen Borders Code (SBC - Regulation (EU) 2016/399)[7] to meet new standards and the EU's ambition to achieve its "smart borders" strategy. Although this strategy was launched more than two decades ago, the catalyst for the accelerated deployment of modern technologies such as ABC in border control was Regulation (EU)

2017/458[8], which amended the SBC by adding the requirement for systematic checks on citizens enjoying the right of free movement across EU borders. According to this regulation, systematic checks entail screening against SIS, national information systems, and Interpol databases. This new requirement predictably caused delays in airport border checks and essentially necessitated ABC systems to facilitate passenger flow without compromising security.

Regulation (EU) 2017/2225 plays a key role in the legal integration of ABC hardware by providing the explicit mandate for the use of self-service systems and automated border control modules. The technological architecture of ABC is designed to perform two-step authentication. Upon entering the module, the passenger places their electronic travel document on the scanner; the system reads the Machine-Readable Zone (MRZ) of the document and, using contactless RFID technology, extracts the information from the document's chip, including the digitally recorded facial image. The second step is on-site biometric capture. Specialized cameras conduct a geometric analysis of the passenger's face and compare this data with the image extracted from the chip. Built-in liveness detection technology prevents fraud attempts using static photos, videos, glasses, or masks. Upon a complete match, the system instantly performs an automated check in security databases. Naturally, ABC is not entirely devoid of human intervention, but human involvement is minimized and consists of a border guard supervising the system. In standard practice, the border guard only acts by providing verbal instructions on how to use the ABC or when a hit is established in SIS, national information systems, or Interpol databases.

The implementation of the EES was regulated by two acts that completely changed the operational reality on the frontline at airport BCPs. The first regulation[9] is the establishing act creating the EES. It outlines what data must be collected, the rules for calculating the passenger's authorized stay, the alerts the EES will generate/send, and which national authorities will have access to the system. The second legal act is Regulation (EU) 2017/2225, which practically deploys the EES at the border and formulates the operational procedure for it. It amends the SBC by abolishing the requirement to stamp the passports of third-country nationals and adding the possibility for these citizens to use self-service systems (kiosks) and ABC for the actual border crossing. The primary reform introduced by the EES is the complete elimination of manual passport stamping—a process that has historically been a source of delay for border guards and an opportunity for data manipulation.

In practice, the EES functions as a centralized electronic register for third-country nationals. When passing through an ABC gate or a standard border check booth, the system records the passenger's full name, document type, four fingerprints, and facial image. The system's built-in algorithm automatically calculates the duration of the authorized stay according to the 90/180-day rule. Additionally, the system tracks the cumulative history of entries into the Schengen area and generates and sends instant notifications to competent national authorities upon detecting overstayers.

Through ABC and EES, border processes are optimized in two areas: BCP throughput capacity and risk reduction. By transferring routine checks to ABC, subjective human error is minimized. The border guard is no longer burdened with manually counting whether the passenger complies with their authorized stay via passport stamps, or with visually assessing the similarity between a photo and a face, where fatigue (e.g., during heavy traffic at 03:00 AM) is a serious risk factor. Thanks to these two systems, the processing time per passenger can be significantly reduced, increasing the throughput capacity of airport terminals during peak hours without compromising security. It is important to note that the human factor is not eliminated but redirected—officers are freed from basic routine activities to concentrate on risks and specialized tasks, such as a database hit, a software-generated entry refusal, or a risk indicator that necessitates a thorough second-line check.

Interim conclusion: The second stage of forming the passenger's "digital twin" adds their physical and biometric identity. The merging of the biographical and behavioral profile generated by ETIAS and API/PNR with the real biometric data from the EES and ABC closes the profiling loop. Thus, the "digital twin" ceases to be merely a predictive model and becomes proof of identity and the legality of the individual's stay on-site.

IV. INTEROPERABILITY: THE INTEGRATION OF THE "DIGITAL TWIN"

For the "digital twin" concept to function effectively in a dynamically changing high-risk environment, its construction cannot rely on fragmented information. Prior to the smart borders concept, the architecture of European information systems was characterized by structural isolation. The systems operated independently of one another and did not communicate. This inability to instantly exchange information created a severe vulnerability. For example, it was possible for an individual to be registered in different databases under different identities without the discrepancy being effectively detected. In the context of this study, a fragmented database

is incapable of creating a comprehensive and up-to-date "digital twin"; it only creates an illusion of control, not real security.

Here, it is important to make a conceptual clarification. In official EU documents, the term "digital twin" does not appear. The EU's objective is not defined as creating a virtual model for its own sake, but rather achieving "interoperability" to eliminate informational blind spots, all in the name of the overarching goal—"smart borders." Nevertheless, the "digital twin" concept is the most accurate academic and theoretical prism through which the final result of the EU's "smart borders" can be analyzed. In practice, despite not using this specific terminology, by achieving interoperability between systems, the EU *de facto* constructs an architecture that possesses all the functional characteristics of a perfect "digital twin."

Overcoming the vulnerability of fragmented databases is ensured through two EU regulations[10][11] that shape the legal and technological framework of interoperability. The core of this new architecture is the Common Identity Repository (CIR). It represents not just another new database, but a powerful integrating layer containing a massive volume of information. The CIR extracts biographical data and biometric identifiers from all European systems, including EES, ETIAS, the Visa Information System (VIS) etc., and merges them into a single, encrypted information block that can be used by law enforcement authorities within the EU territory.

It is precisely within the CIR that the true merging of information and final shaping of the profile occurs. The biographical and behavioral framework pre-constructed via ETIAS and national API/PNR systems is strictly linked to the real biometric identity of the individual, captured at the airport via ABC and EES. Consequently, the "digital twin" becomes a complete, up-to-date, and tamper-proof virtual model of the passenger. In the spirit of a digital and circular future, this profile is not static. It is dynamic, and with every subsequent border crossing, new booking, or change in visa status, the information automatically flows through the systems and, upon reaching the CIR, updates the profile in real time.

This deep integration demands a complete paradigm shift in border security: a transition from reactive to proactive analysis and profiling. In the traditional model, the border guard acted reactively—checking the document only when the passenger physically stood before them at the booth. With the integrated "digital twin," the systems act preemptively. Crucially, to prevent identity duplication, a Multiple-Identity Detector (MID) has been created. Through the MID, the CIR is scanned automatically, and an instant alert is triggered if a fraud attempt is detected—for example, if a

person entering with a passport from one country via ABC exists under a different identity and with different biometric data in the Europol, SIS, or national databases.

Interim conclusion: The complete digital profile allows security services to filter high-risk passengers and analyze the threat before the individual makes contact with frontline border guards. Thus, interoperability proves that modern EU air border management relies not on building higher physical barriers, but on creating data-driven smart borders. It is a protective net in which the "digital twin" is the primary prevention tool.

V. TECHNOLOGICAL AND REGULATORY CHALLENGES. FORECAST

One of the greatest challenges is protecting the personal data of all individuals who will interact in some form with the new EU systems. The EES, for example, will collect and store a large volume of sensitive information, including biometric data—fingerprints and facial images. These data are classified as a special category of highly sensitive information, and their mass collection and centralized storage in the CIR creates the risk of the system turning into a mass surveillance tool. Regulation (EU) 2017/2226 sets clear requirements to guarantee human rights and fundamental freedoms by stipulating strict data retention periods and an access hierarchy, but ensuring security and preventing data misuse must remain among the top priorities. The human factor plays a critical role here. The technological infrastructure may be encrypted and secure, but the frontline officers, PIU analysts, and system operators are the ones who must apply ethical norms and prevent unauthorized access to or abuse of virtual profiles. In the future, continuous improvement of data protection mechanisms and strict enforcement of regulations will be necessary. We must not overlook the fact that the data stored in the CIR will be of high intelligence interest to third-country agencies, inevitably necessitating active counterintelligence operations to thwart any attempt at unauthorized use of the CIR. This is why the rules for subsequent analysis of who used the CIR and when should be strengthened.

Another major challenge is related to the need of providing adequate training for the personnel using the new systems. Because the EES, for example, will change basic border control procedures, officers must be well-prepared to work with the new technology, including troubleshooting technical issues and handling new operational protocols. This process is key to the efficient functioning of the system and minimizing human error. Given the need for increasingly tech-savvy personnel, it would be

beneficial to introduce a uniform digital competency requirement at the EU level for border guards performing border checks. The global trend towards digitization dictates the need for border control services to possess a sufficient number of trained personnel who face no difficulties working with digital (electronic) products. Achieving the EU strategy of Integrated Border Management includes the mission of "smart borders" that utilize a wide array of information systems, and this is fundamental to achieving security within the EU territory.

As a forecast, we can note the inevitable evolution of EU security systems - their future integration with Artificial Intelligence (AI). The collection and storage of millions, if not billions, of records in the CIR provide a perfect information environment for training machine learning algorithms. AI holds the potential to transform proactive analysis, and this is an ongoing trend. Instead of human operators searching for connections between suspicious individuals, neural networks can perform multi-dimensional network analysis on API/PNR datasets in real time. This would enable the automated recognition of complex, hidden behavioral patterns used by human trafficking or smuggling networks that remain invisible to conventional filters. However, this operational potential is strictly limited by the current EU regulatory framework. Under European law[12], the use of AI in migration management and border control is classified as a "high-risk". The most severe restriction is linked to the inability of algorithms to transparently explain the logic behind their calculations. In European law, refusing entry at the border is an administrative act subject to judicial appeal and requires definitive factual motives. A border guard cannot deny access to the Schengen territory based solely on the argument that the software calculated a high-risk percentage for a given individual. Therefore, the legislation imposes the requirement to maintain the "human-in-the-loop" principle. The "digital twin" and its associated algorithms can filter databases, trigger alerts, and direct attention, but the final decision regarding the passenger's fate at the border remains the exclusive responsibility of the human factor.

Interim conclusion: The evolution of security systems and their future integration with AI offer new opportunities for proactive analysis, but at present, they are strictly limited by European legislation in the fields of AI and data protection. Overcoming future challenges in EU border security must involve the preparation of highly qualified, digitally competent personnel capable of managing new technological processes while strictly adhering to the "human-in-the-loop" principle. This is because effective

border security depends not only on financial investments in software and hardware but also on the people operating them.

VI. CONCLUSION

Implementing the "digital twin" concept into the architecture of European border security marks a transition from traditional, static check methods to dynamic and proactive risk management. This study demonstrates that the "digital twin" is far from just an abstract IT concept or an isolated software solution. It represents the new paradigm in the integrated management of EU air borders and is achievable thanks to the deep interoperability between advance data analysis systems, automated biometric platforms, and the CIR.

The critical analysis of this high-tech network outlines a clear final message: digitization and the deployment of complex systems do not aim to eliminate the role of the human factor on the frontline. On the contrary, automation frees up resources and transforms the border guard's function toward greater efficiency. They are no longer burdened with mechanical routine tasks; instead, they become key analysts equipped with a powerful tool for making important strategic decisions in real time based on verified data. Ultimately, EU border security in an era of increased global mobility depends precisely on this technological synergy—the precision of the constructed "digital twin" and the irreplaceable professional judgment of the human, tailored to each individual case.

References:

1. Regulation (EU) 2018/1240 of the European Parliament and of the Council of 12 September 2018 establishing a European Travel Information and Authorisation System (ETIAS)
2. Regulation (EU) 2018/1241 of the European Parliament and of the Council of 12 September 2018 amending Regulation (EU) 2016/794 for the purpose of establishing a European Travel Information and Authorisation System (ETIAS)
3. Regulation (EU) 2025/12 of the European Parliament and of the Council of 19 December 2024 on the collection and transfer of advance passenger information (API) for enhancing and facilitating external border controls, amending Regulations (EU) 2018/1726 and (EU) 2019/817 and repealing Council Directive 2004/82/EC
4. Regulation (EU) 2025/13 of the European Parliament and of the Council of 19 December 2024 on the collection and transfer of advance passenger

information for the prevention, detection, investigation and prosecution of terrorist offences and serious crime, and amending Regulation (EU) 2019/818
5. Directive (EU) 2016/681 of the European Parliament and of the Council of 27 April 2016 on the use of passenger name record (PNR) data for the prevention, detection, investigation and prosecution of terrorist offences and serious crime
6. Regulation (EU) 2017/2225 of the European Parliament and of the Council of 30 November 2017 amending Regulation (EU) 2016/399 as regards the use of the Entry/Exit System
7. Regulation (EU) 2016/399 of the European Parliament and of the Council of 9 March 2016 on a Union Code on the rules governing the movement of persons across borders (Schengen Borders Code)
8. Regulation (EU) 2017/458 of the European Parliament and of the Council of 15 March 2017 amending Regulation (EU) 2016/399 as regards the reinforcement of checks against relevant databases at external borders
9. Regulation (EU) 2017/2226 of the European Parliament and of the Council of 30 November 2017 establishing an Entry/Exit System (EES) to register entry and exit data and refusal of entry data of third-country nationals crossing the external borders of the Member States and determining the conditions for access to the EES for law enforcement purposes, and amending the Convention implementing the Schengen Agreement and Regulations (EC) No 767/2008 and (EU) No 1077/2011
10. Regulation (EU) 2019/817 of the European Parliament and of the Council of 20 May 2019 on establishing a framework for interoperability between EU information systems in the field of borders and visa and amending Regulations (EC) No 767/2008, (EU) 2016/399, (EU) 2017/2226, (EU) 2018/1240, (EU) 2018/1726 and (EU) 2018/1861 of the European Parliament and of the Council and Council Decisions 2004/512/EC and 2008/633/JHA
11. Regulation (EU) 2019/818 of the European Parliament and of the Council of 20 May 2019 on establishing a framework for interoperability between EU information systems in the field of police and judicial cooperation, asylum and migration and amending Regulations (EU) 2018/1726, (EU) 2018/1862 and (EU) 2019/816
12. Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised 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)

E-COMMERCE ADOPTION BARRIERS AMONG BULGARIAN SMEs: INFRASTRUCTURE, DIGITAL SKILLS AND REGULATORY BURDEN COMPARED WITH EU AVERAGES

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Abstract: *In a technology-rich business environment, small and medium-sized enterprises need functional online sales channels to stay competitive in the European Single Market. Bulgaria ranks last among EU member states in e-commerce turnover, at 8 per cent of total business revenue, and only about half of its SMEs reach the basic digital intensity level. The purpose of this study is to identify which barriers weigh most on e-commerce adoption by Bulgarian SMEs and how far these barriers differ from EU averages. The analysis uses harmonised secondary data from Eurostat and the European Commission for 2020-2025, focusing on three domains: broadband connectivity, workforce digital skills, and VAT compliance under the One Stop Shop regime. The findings show that the infrastructure gap has largely closed at the national level, while a wide and persistent digital-skills deficit and OSS-related compliance costs remain the binding constraints. Targeted skills programmes and a graduated OSS compliance regime are identified as the priority policy levers.*

Keywords: *e-commerce adoption, SMEs, digital transformation, Bulgaria, European Union, One Stop Shop, TOE framework*

1. Introduction

E-commerce adoption among small and medium-sized enterprises (SMEs) differs substantially across the European Union, and Bulgaria consistently falls near the bottom of the distribution. Eurostat (2024) records 15.1 per cent of Bulgarian enterprises selling online in any form; the EU average stands at 23.8 per cent, and only Romania has a lower share. Online sales generate no more than 8 per cent of total business turnover in Bulgaria, compared with 19.1 per cent across the EU. Digital intensity data reinforce this picture: 49.9 per cent of Bulgarian SMEs reach the basic

digital intensity threshold, while 72.9 per cent of EU firms do (European Commission, 2025a). These gaps are sufficiently wide and persistent to indicate a structural rather than a short-term lag.

The COVID-19 crisis did not create this deficit; it made it visible. For SMEs in less developed EU member states, e-commerce rapidly shifted from a strategic option to a condition of survival (OECD, 2021; Rupeika-Apoga et al., 2022). Yet most Bulgarian small firms lacked the basic resources for this shift: a functioning online sales channel, staff able to manage it, and a delivery chain beyond the local market, as documented by Kolupaieva and Tiesheva (2023) and Skare et al. (2023).

Several structural barriers sustain the disparity. Rural broadband reaches 86.6 per cent of Bulgarian households; the EU rural average is 92.8 per cent (Eurostat, 2025). The skills picture is considerably worse: 38.3 per cent of the Bulgarian population possesses at least basic digital competences, compared with 60.4 per cent in the EU (Eurostat, 2025). A further constraint arises from regulatory compliance: small firms attempting cross-border e-commerce face administrative costs under the One Stop Shop (OSS) VAT system that Tofan and Bostan (2022) identify as a measurable deterrent for micro-enterprises.

Tornatzky and Fleischer (1990) built a model around three adoption drivers: the technology itself, the organisation attempting to use it, and the external environment. Systematic reviews confirm that this Technology-Organisation-Environment (TOE) framework still holds explanatory weight, though Central and Eastern European (CEE) economies add complications not always present elsewhere: digital talent is hard to recruit, rural networks remain patchy, and public support programmes often exist on paper more than in practice (Loo et al., 2025; Ntsiful et al., 2023).

Research that focuses specifically on Bulgaria remains scarce. Kyosova (2025) puts the share of agricultural micro-enterprises with an online store at 1.94 per cent. Takov (2024) finds that digital adoption in Bulgaria trails Western European averages and falls short of regional peers such as Croatia and Estonia. To the best of the author's knowledge, no study has assembled the full range of Bulgarian e-commerce barriers and measured all three simultaneously against EU-level benchmarks within a single analytical framework. The present paper addresses that gap.

Two research questions guide the analysis. First, which barriers carry the most weight in constraining e-commerce adoption among Bulgarian SMEs? Second, how far do Bulgarian indicators fall below EU averages across the three identified domains? The data are drawn from Eurostat, the

European Commission, and the Bulgarian National Statistical Institute and cover the period 2020 to 2025.

2. Literature Review

The TOE framework has proven durable as an analytical tool for e-commerce adoption research. Tornatzky and Fleischer (1990) proposed it to explain why some firms adopt new technologies while others in similar markets do not. The model separates technology factors from organisational ones and treats the external environment as a distinct third force. Loo et al. (2025) confirm in a recent systematic review that TOE remains the most frequently applied framework in SME e-commerce studies. The framework accommodates cross-country variation, which is central to a study comparing Bulgarian SMEs with EU averages, and allows for partial adoption, firms may adopt late, adopt selectively, or adopt and then pull back (Nazir and Roomi, 2021).

On the technology side, broadband infrastructure is the most cited barrier. Grigorescu et al. (2021) map the digital divide across EU regions and place rural Southern and Eastern Europe at the tail end of the distribution. Brodny and Tutak (2022) and Skare et al. (2023) use DESI data to rank member states by connectivity and confirm that Bulgaria sits persistently near the bottom. Tislenko (2024) adds that connectivity alone is insufficient: without affordable cloud services and payment processing tools, broadband access does not translate into functional e-commerce for micro-enterprises.

Organisational barriers centre on digital skills and firm size. Eurostat (2025) places Bulgaria last among EU member states on basic digital competences, with 38.3 per cent of the population achieving at least the basic level against an EU average of 60.4 per cent. The gap widens at higher proficiency levels: Bulgaria and Romania record the lowest above-basic digital skills coverage in the EU, at 11.8 and 11.1 per cent respectively, against an EU average of 31.4 per cent (Eurostat, 2025). Ragazou et al. (2022) find that countries with lower human capital scores report lower e-commerce revenues. Clemente-Almendros et al. (2024) report a fourfold gap in online selling between firms with fewer than ten employees and those with fifty or more. Serban et al. (2020) introduce the concept of digitally vulnerable enterprises, firms meeting fewer than two of the four basic digital intensity criteria, a measure by which nearly half of Bulgarian SMEs qualify.

Cross-border e-commerce adds a regulatory layer. VAT compliance is the most tangible obstacle. The EU launched the One Stop Shop in July

2021 to allow online sellers to register once and report all cross-border B2C sales through a single quarterly return. By the end of 2024, over 153,000 businesses were registered for the Union OSS, and over EUR 33 billion in VAT was declared across all OSS/IOSS schemes, a 26 per cent increase year-on-year (European Commission, 2025b). Zidkova and Kebrtova (2022) evaluate the system and find that it reduces paperwork but does not remove it: sellers still need to track 27 different VAT rate structures and maintain destination-specific records. Tofan and Bostan (2022) estimate that compliance costs fall disproportionately on micro-enterprises, where one cross-border sale may not cover the fixed expense of staying compliant.

The available evidence on Bulgaria remains fragmented. Infrastructure gaps, skills deficits, and regulatory friction have each been documented separately; their combined effect on Bulgarian SME e-commerce adoption has not been measured against EU benchmarks within a single analytical framework. The present study fills this gap by treating all three domains within a single comparative framework.

3. Methodology

All data used are secondary. No primary fieldwork was conducted. Eurostat and the European Commission publish harmonised indicators covering all 27 member states. Cross-country comparison is therefore methodologically consistent by design. The observation window spans 2020 to 2025. It captures the pre-pandemic baseline, the post-COVID digital shift, and the early years of Bulgaria's Digital Transformation Strategy for 2024–2030.

The observation window runs from 2020 to 2024, with the most recent available observations extending to 2025 where survey cycles permit. This period captures the pre-pandemic baseline, the post-COVID reconfiguration of digital commerce, and the early phase of implementation of Bulgaria's Digital Transformation Strategy for 2024-2030. It also spans the transition from the DESI framework to the Digital Decade monitoring cycle, allowing legacy indicators to be aligned with the new 2030 policy targets. Where indicators are collected biennially on different cycles - digital skills in odd years, ICT training in even years - the most recent available observation is used for each indicator, with the reference year noted in the respective table.

Three data sources underpin the analysis: Eurostat (enterprise e-commerce use, broadband coverage, and digital tools by firm size); the European Commission’s Digital Economy and Society Index (DESI) and

subsequent Digital Decade reports, covering connectivity and human capital; and the National Statistical Institute of Bulgaria for regional internet access and enterprise structure. These sources were selected because they are methodologically harmonised across countries and years and provide sufficient granularity to construct Bulgaria-EU indicator pairs for the three domains of interest.

The domain selection follows a pragmatic rather than exhaustive logic. The literature identifies a wide set of potential e-commerce barriers, ranging from logistics performance and payment systems to access to finance and organisational culture. In the Bulgarian context, however, three domains stand out as both structurally important and measurably comparable with EU averages: broadband infrastructure, digital skills, and VAT compliance for cross-border e-commerce. Infrastructure and skills correspond to the technology and organisation pillars of the TOE framework, while the VAT regime - in particular the One Stop Shop - captures a core element of the regulatory environment. Other relevant factors such as access to working capital, parcel delivery performance or platform dependence are acknowledged but lie beyond the scope of this paper, mainly because no harmonised quantitative indicators exist for Bulgaria and the EU that would allow a consistent 2020-2024 comparison. The findings should therefore be interpreted as relating to these three measurable domains rather than to the full spectrum of possible barriers.

The analysis uses the Digital Economy and Society Index (DESI) and its successor, the Digital Decade monitoring framework, to characterise Bulgaria's position in connectivity and human capital. While DESI has become the de facto standard for benchmarking EU member states, several methodological limitations must be acknowledged. The index aggregates a large number of highly correlated indicators, which can blur the distinction between conceptually different dimensions and distort country rankings. It is designed as a broad status indicator rather than a micro-level diagnostic tool and is not tailored to capture sector-specific barriers or firm-level heterogeneity. In addition, DESI is Eurocentric and largely use-oriented, focusing on connectivity and basic usage rather than deeper measures of digital value creation, such as software-based innovation or monetisation capabilities. For these reasons, DESI scores are used in this paper only as a contextual benchmark and are complemented by more granular Eurostat series on e-commerce incidence and turnover.

All e-commerce indicators used in this paper are drawn from Eurostat's annual survey on ICT usage and e-commerce in enterprises, which covers firms with at least ten employees. The survey is conducted by national

statistical offices in the first months of each year, with reference to the preceding calendar year for questions on e-commerce. Data are collected and validated under harmonised metadata and quality standards, which support cross-country comparability but also imply a focus on formal enterprises; micro-firms below ten employees, which constitute a substantial share of Bulgarian businesses, are not captured. This coverage limitation suggests that the results are likely to understate the true extent of structural barriers for the smallest enterprises.

Digital infrastructure is captured through fixed broadband penetration rates and the DESI connectivity score. Human capital and digital skills are measured using Eurostat indicators on basic and above-basic digital competences, together with the DESI human capital dimension. Regulatory burden is assessed through the secondary literature rather than a dedicated statistical series, since no public dataset records OSS compliance costs at firm level. All indicators are presented as Bulgaria-EU pairs with the absolute gap reported. The analysis is deliberately descriptive and comparative: no inferential statistics are applied. No additional data transformation or imputation was applied; Eurostat series flags indicating estimation or methodological breaks are noted where relevant. The main limitation is that aggregate indicators cannot reveal intra-country heterogeneity or firm-level decision processes.

The results are presented in three parts, following the analytical domains set out in the methodology.

4. Findings

4.1 Digital Infrastructure

Table 1 summarises the main connectivity indicators.

Indicator	Bulgaria	EU average	Gap (pp)
Households with internet access (2025)	92.8%	94.7%	-1.9
Rural households with internet access (2025)	86.6%	92.8%	-6.2
Urban households with internet access (2025)	97.0%	95.5%	+1.5
Enterprises with internet access (2025)	96.4%	99.0%	-2.7

Table 1. Digital infrastructure: Bulgaria vs EU average (2025). Source: Eurostat, isoc_ci_in_h (updated 17 April 2026); Eurostat, isoc_ci_in_en2 (updated 27 February 2026). All data refer to 2025.

Bulgaria now matches the EU average on overall household internet access at the national level. Urban access (96.4%) marginally exceeds the EU average of 95.5%, while rural coverage lags by 6.2 percentage points.

The territorial divide, not the national aggregate, is where the infrastructure deficit concentrates. The rural gap persists despite overall progress at national level. At the enterprise level, 96.4 per cent of Bulgarian businesses have internet access, a figure that trails the EU average of 99.0 per cent by 2.7 percentage points (Eurostat, 2025).

4.2 Human Capital and Digital Skills

Table 2 presents the skills-related indicators.

Indicator	Bulgaria	EU average	Gap (pp)
Adults with at least basic digital skills (16-74) (2025)	38.3%	60.4%	-22.1
Adults with above-basic digital skills (2025)	11.8%	31.4%	-19.6
Enterprises providing ICT training (2024)	9.1%	22.4%	-13.3
ICT specialists in employment (2024)	4.6%	5.0%	-0.4

Source: Eurostat (2025), dataset isoc_sk_dskl_i21; Eurostat (2024), dataset isoc_ske_ittn2; European Commission (2025a), Digital Decade Country Report.

The skills gap is considerably wider than the infrastructure gap. Only 38.3 per cent of the Bulgarian population holds at least basic digital competences, compared with 60.4 per cent in the EU, a gap of 22 percentage points, placing Bulgaria 26th out of 27 EU member states (Eurostat, 2025). Bulgaria and Romania record the lowest above-basic digital skills coverage in the EU, at 11.8 and 11.1 per cent respectively, against an EU average of 31.4 per cent (European Commission, 2025a). Only 9.1 per cent of Bulgarian enterprises provide any form of ICT training to their employees, against 22.4 per cent in the EU. Over the 2023-2025 period Bulgaria recorded a 3.8 per cent annual growth in basic digital skills, yet given the distance to be covered, this rate is insufficient to close the gap before the EU's 2030 Digital Decade target of 80 per cent basic skills coverage.

4.3 Regulatory Burden and VAT Compliance

No public dataset records OSS compliance costs at firm level. The analysis therefore draws on the secondary literature and the structural features of the regime. The One Stop Shop launched in July 2021. It allows businesses to file a single quarterly VAT return for all EU cross-border B2C sales with their home tax authority. By end-2024, over 153,000 businesses were registered for the Union OSS. EUR 33 billion in VAT was declared across all OSS and IOSS schemes, a 26 per cent increase year-on-year (European Commission, 2025b).

Despite this simplification, sellers must still monitor 27 different VAT rate structures, maintain destination-specific records for ten years, and invest in compliance software or advisory services (Zidkova and Kebrtova,

2022). Tofan and Bostan (2022) estimate that these costs fall disproportionately on the smallest firms: a micro-enterprise making only a handful of cross-border sales per month may spend more on staying compliant than it earns from those transactions. The EUR 10,000 annual threshold creates a cliff effect: sales below it are administratively simple, but above it a step change in reporting complexity discourages experimentation by Bulgarian micro-enterprises already operating on thin margins with limited back-office capacity.

5. Discussion

The three barriers do not weigh equally. Infrastructure has narrowed the gap with EU averages. The remaining deficit is territorial, not national. Digital skills have not followed the same trajectory. Basic competence coverage stands 22 percentage points below the EU average. That gap has not closed. Regulatory burden falls between the two: OSS compliance is irrelevant for firms that sell only domestically, but it becomes a fixed cost that small cross-border sellers often cannot absorb.

Of the three domains, human capital emerges as the most binding constraint. Loo et al. (2025) note in their systematic review that organisational factors tend to outweigh purely technological ones in less developed economies; Nazir and Roomi (2021) make the same observation for emerging markets. Bulgaria fits this pattern precisely: the country has made measurable progress on connectivity, but the workforce is not yet equipped to use it. Nine out of ten Bulgarian enterprises provide no ICT training at all. Without skilled staff, to build a product catalogue, manage digital payments, respond to online enquiries, or read analytics dashboards, broadband access alone does not translate into functional e-commerce operations.

Bulgaria's position within the CEE context deserves specific attention. The country is not a simple instance of a general less developed economy pattern: it is an outlier even within the region. Skare et al. (2023) show in their DESI-based cross-country analysis that countries which score low on digitalisation tend to remain there over time, suggesting structural lock-in rather than a simple developmental lag. Takov (2024) finds that Bulgaria's digital adoption trails not only Western European averages but also regional peers such as Croatia and Estonia, which have comparable income levels but markedly better skills profiles. The mechanism is partly self-reinforcing: firms that cannot find digitally skilled employees do not invest in e-commerce platforms, and the absence of e-commerce demand in turn reduces the labour market incentive to develop those skills. Breaking this

feedback loop requires external intervention, whether through public training programmes, subsidised e-commerce onboarding, or EU-funded digital voucher schemes.

The three barriers do not operate independently; they reinforce one another in ways that make the aggregate constraint larger than the sum of its parts. A Bulgarian micro-enterprise in a rural municipality faces inferior broadband (infrastructure barrier), has owners and employees unlikely to hold above-basic digital skills (human capital barrier), and, if it tests cross-border sales, confronts an OSS compliance obligation that requires either specialist knowledge or paid assistance (regulatory barrier). Each barrier alone might be manageable. When all three are present simultaneously, as they frequently are in rural Bulgaria, the combination effectively prices micro-enterprises out of e-commerce. This compounding effect has important implications for policy sequencing: addressing only one barrier at a time may yield limited returns if the other two remain binding.

The regulatory findings take on added significance given the forthcoming EU reforms. The VAT in the Digital Age (ViDA) package is projected to reduce administrative and compliance costs for EU traders by over EUR 4.1 billion per year over the next decade (European Commission, 2024b). For Bulgarian SMEs, the most relevant ViDA element is the extension of single VAT registration and planned digital reporting obligations, which could eventually automate much of the OSS compliance workflow. However, ViDA's benefits depend on firms having the digital skills to use the new systems. A firm without above-basic digital competences in its workforce is unlikely to benefit from automated e-invoicing or digital VAT returns. Skills investment is therefore a prerequisite not only for e-commerce adoption in the narrow sense, but also for the successful uptake of regulatory simplifications already in the pipeline.

Two concrete policy implications follow. First, the most productive marginal investment may no longer be in broadband roll-out but in targeted digital skills programmes for SME owners and employees. National broadband coverage is approaching EU levels; the skills deficit is not. Programmes analogous to the Estonian digital jump initiative or the Czech and Hungarian acceleration schemes, which recorded the EU's highest year-on-year improvements in basic digital skills in the 2025 DESI cycle (European Commission, 2025a), offer transferable models. EU Structural Funds and the Recovery and Resilience Facility provide financing vehicles that Bulgaria has not yet fully utilised for SME digital upskilling at scale. Second, a graduated OSS compliance regime, with lighter quarterly reporting obligations for micro-enterprises in their first years of cross-border operation,

could reduce the cliff effect that currently discourages experimentation. The EU VAT Committee's earlier work on SME exemption schemes provides legislative precedent for differentiated treatment (European Commission VAT Committee, 2018).

6. Conclusion

The evidence points in one direction. Bulgarian SME e-commerce adoption is not held back by a single missing input; it is held back by the compounding of three deficits that reinforce one another at the firm level. Infrastructure has largely caught up with EU averages in urban areas; the remaining rural gap, at 6.2 percentage points, is real but addressable through existing EU funding mechanisms. Digital skills have not caught up. At 38.3 per cent basic competence coverage against an EU average of 60.4 per cent, Bulgaria carries a structural deficit that years of incremental progress have not closed. Fewer than one in ten Bulgarian enterprises provides ICT training to its workforce. These are not transitory numbers.

VAT compliance under the OSS adds a third layer. The EUR 10,000 threshold is sharp: below it, cross-border selling is administratively light; above it, the fixed compliance costs can exceed the margin on a small seller's entire cross-border revenue for the month. The cliff does not stop large firms. It stops micro-enterprises from experimenting.

The three deficits do not operate in isolation. A rural firm with below-average connectivity, a workforce without above-basic digital skills, and no back-office capacity to manage OSS reporting faces a combination that no single policy lever resolves. This compounding effect is the central finding of the present analysis.

Two policy directions follow from the evidence. Skills investment is the most productive marginal allocation: broadband is approaching EU levels, compliance can be simplified through ViDA, but neither investment pays off if the workforce cannot operate the underlying systems. A graduated OSS compliance regime, with lighter obligations for micro-enterprises in their first years of cross-border activity, would lower the threshold cliff without requiring legislative overhaul. The ViDA package creates the structural conditions for both reforms; whether Bulgaria uses that window depends on implementation choices that remain national.

The analysis rests on aggregate secondary data and cannot capture firm-level variation or the precise cost of regulatory compliance for individual enterprises. These are real boundaries. Within them, the benchmarking presented here establishes a measurable baseline against which the effect of

Bulgaria's Digital Transformation Strategy 2024-2030 can eventually be assessed.

References:

1. Brodny, J. and Tutak, M. (2022) Analyzing the level of digitalization among the enterprises of the European Union member states and their impact on economic growth, Journal of Open Innovation: Technology, Market, and Complexity, 8(2), 70. DOI: 10.3390/joitmc8020070.
2. Clemente-Almendros, J.A., Popescu-Nicoar, D. and Pastor-Sanz, I. (2024) Digital transformation in SMEs: understanding its determinants and size heterogeneity, Technology in Society, 77, 102483. DOI: 10.1016/j.techsoc.2024.102483.
3. European Commission (2024a) Report on the State of the Digital Decade 2024. Brussels: European Commission.
4. European Commission (2024b) VAT in the Digital Age (ViDA) - Implementation Strategy. Brussels: European Commission.
5. European Commission (2025a) Report on the State of the Digital Decade 2025. Brussels: European Commission.
6. European Commission (2025b) Report on the application of the VAT e-commerce package for 2024. Available at: https://vat-one-stop-shop.ec.europa.eu/news-reports/report-application-vat-e-commerce-package-2024_en (Accessed: 21 April 2026).
7. European Commission VAT Committee (2018) Special scheme for small enterprises under the VAT Directive. Brussels: European Commission.
8. Eurostat (2024) E-commerce statistics - Statistics Explained. Luxembourg: Publications Office of the European Union.
9. Eurostat (2025) ICT usage and digital skills statistics [datasets: isoc_sk_dskl_i21; isoc_ci_in_h; isoc_ci_in_en2]. Luxembourg: Publications Office of the European Union. Available at: https://ec.europa.eu/eurostat/databrowser (Accessed: 22 April 2026).
10. Grigorescu, A., Pelinescu, E., Ion, A.E. and Dutcas, M.F. (2021) Human capital in digital economy: an empirical analysis of Central and Eastern European countries from the European Union, Sustainability, 13(4), 2020. DOI: 10.3390/su13042020.
11. Kolupaieva, I. and Tiesheva, L. (2023) Asymmetry and convergence in digital technologies in EU, Equilibrium. Quarterly Journal of Economics and Economic Policy, 18(3), pp. 687-716. DOI: 10.24136/eq.2023.022.
12. Kyosova, A. (2025) E-commerce adoption trends in Bulgarian agriculture, in Proceedings of the International Conference on Business Excellence (PICBE), pp. 4963-4974. DOI: 10.2478/picbe-2025-0379.
13. Loo, M.K., Ramachandran, S. and Raja Yusof, R.N. (2025) Systematic review of factors and barriers influencing e-commerce adoption among SMEs over the last decade: a TOE framework perspective, Journal of the Knowledge Economy, 16(2), pp. 9624-9648. DOI: 10.1007/s13132-024-02257-5.

14. Nazir, S. and Roomi, M.A. (2021) Barriers to adopting electronic commerce for small and medium-sized enterprises in emerging economies, Emerging Markets Journal (EMAJ), 10(2), pp. 44-55. DOI: 10.5195/emaj.2020.203.
15. Ntsiful, A., Osei, H.V., Agyapong, G.K.Q. and Kwarteng, M.A. (2023) Extending UTAUT with competitive pressure for SMEs digitalization adoption in two European economies, Aslib Journal of Information Management, 75(6), pp. 1039-1064. DOI: 10.1108/AJIM-11-2022-0482.
16. OECD (2021) The Digital Transformation of SMEs. Paris: OECD Publishing. DOI: 10.1787/bdb9256a-en.
17. Ragazou, K., Passas, I. and Sklavos, G. (2022) Investigating the strategic role of digital transformation path of SMEs in the era of COVID-19: a bibliometric analysis using R, Sustainability, 14(18), 11295. DOI: 10.3390/su141811295.
18. Rupeika-Apoga, R., Petrovska, K. and Bule, L. (2022) The effect of digital orientation and digital capability on digital transformation of SMEs during COVID-19, Journal of Theoretical and Applied Electronic Commerce Research, 17(2), pp. 669-685. DOI: 10.3390/jtaer17020035.
19. Serban, A.C., Lytras, M.D. and Alhalabi, W. (2020) Mapping the foundations of a digitally vulnerable society, PLOS ONE, 15(7), e0232032. DOI: 10.1371/journal.pone.0232032.
20. Skare, M., de Obesso, M.M. and Ribeiro-Navarrete, S. (2023) Digital transformation and European small and medium enterprises (SMEs): a comparative study using digital economy and society index data, International Journal of Information Management, 68, 102594. DOI: 10.1016/j.ijinfomgt.2022.102594.
21. Takov, B. (2024) State and barriers to the digitalization of small and medium-sized enterprises in Bulgaria, Strategies, 1(special issue), pp. 197-210. DOI: 10.53656/str2024-1s-13-sta.
22. Tislenko, M.I. (2024) Digital divide in the European Union: assessing spatial disparities and neighbourhood effects, Journal of the Geographical Institute Jovan Cvijic SASA, 74(2), pp. 181-197. DOI: 10.2298/IJGI2402181T.
23. Tofan, M. and Bostan, I. (2022) Some implications of the development of e-commerce on EU tax regulations, Laws, 11(1), 13. DOI: 10.3390/laws11010013.
24. Tornatzky, L.G. and Fleischer, M. (1990) The Processes of Technological Innovation. Lexington, MA: Lexington Books.
25. Zidkova, H. and Kebrtova, K. (2022) New VAT rules for e-commerce: what will they bring to public budgets?, European Financial and Accounting Journal, 17(2), pp. 49-68. DOI: 10.18267/j.efaj.271.

ЦИФРОВИ ДВОЙНИЦИ НА МОЗЪКА ЧРЕЗ ГЕНЕРАТИВЕН ИЗКУСТВЕН ИНТЕЛЕКТ

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BRAIN DIGITAL TWINS USING GENERATIVE ARTIFICIAL INTELLIGENCE

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Abstract: *Creating digital twins in medicine is a key task for advancing the field. It allows for better and safer testing of substance and procedure effects without the ethical and safety concerns related to real life testing with humans and animals. It also facilitates researchers in modelling certain phenomena such as pathologies, which can improve understanding and serve as a foundation for developing novel treatments. Another key use case is related to education in medicine, especially at university level, where students can practice on virtual models. Generative AI is one of the rapidly developing fields for artificial data generation. Outside of the multimedia applications, generative models can be used to model biological behaviors. Generative models can be trained with brain activity data such as EEG, MEG, fMRI, fNIRS recordings and used to simulate the underlying brain activity. In this paper a brief overview is presented, demonstrating generative AI capabilities for modelling in neyrobiology.*

Keywords: *brain modelling, digital twins, generative artificial intelligence*

I. Цифрови близнаци в медицината

Цифровите близнаци (ЦБ) в медицината представляват виртуални копия на биологични системи [1-8] , които се използват за разнообразни цели – моделиране в изследователски проекти, виртуално тестване на лекарства и медицински процедури, образование [9-11]. За тяхното изграждане се комбинира експертиза от невронауките, изкуствения интелект (ИИ) и дори биофизиката. Моделирането е инструмент за разбиране на процесите в тялото на животните и човека. Съществуването на виртуален близнак помага създаването на по-добри модели като

предоставя рамка за подобрения и експерименти, без недостатъците на експериментите *in vivo*. Проблеми с експериментите върху живи същества са свързани с рискове от усложнения при хирургични намеси, неточност на сканираща техника при запис на биологичните процеси, множество странични влияния върху общото физиологично състояние (което прави резултатите податливи на шум), етични съображения, дискомфорт на пациентите, високи разходи и др. Всички тези недостатъци могат да бъдат елиминирани или смекчени чрез използването на ЦБ. Друга полза от медицинските ЦБ е възможността за разработка на персонализирани лечения, което е в синхрон с глобалната тенденция в медицината за персонализирани подходи за лечение.

II. Генеративен изкуствен интелект

Генеративен изкуствен интелект (ГИИ) е термин, обхващащ модели за машинно обучение (МО), които научават статистическо разпределение на данни от даден вид и генерират извадки, следващи същото разпределение. Най-често се използват невронни модели като Ограничени Болцман машини и Бейсови мрежи, трансформъри и автоенкодъри [12-18]. Обучението им е неконтролирано (без учител) чрез неетикирани данни. Ползват се подходи като контрастна дивергенция (contrastive divergence) и Генеративни вражески мрежи (Generative Adversarial Networks - GAN) [14]. Ограничените Болцман машини и Бейсовите мрежи научават взаимното статистическо разпределение на данни и техните емулирани характеристики. При подхода GAN се ползват две невронни мрежи с противоположни цели – една мрежа, която служи за генератор на данни и една, която служи като класификатор. Генераторът се опитва да възпроизведе входните данни възможно най-точно, а класификаторът се учи да различава оригинални данни от генерирани; двете мрежи са в равновесие на Наш и се обучават взаимно. Нова тенденция са трансформърите, които използват механизми за „внимание“, които се фокусират върху зони на интерес. Графовите невронни мрежи могат да обработват конектомни данни за мрежовата структура на мозъчните клетки. Сред актуалните проблеми на ГИИ е големият изчислителен ресурс, който е необходим, което от своя страна е свързано с големи разходи за инфраструктура и

енергопотребление. Проблемът се адресира чрез тензорни процесори и невроморфен хардуер.

Някои често използвани генеративни модели в мозъчното моделиране са:

- **Вариативни автоенкодъри (Variational Autoencoders - VAE):** позволяват генерирането на нови „синтетични“ мозъчни състояния, които са статистически подобни на истинските. Те помагат за попълване на липсващи данни в цифровия близнак. [18]
- **β-VAE:** използват се за "разплитане" (disentanglement) на скритите променливи – например отделяне на сигнала на специфичен когнитивен процес от фоновия шум. [19]
- **Latent Factor Analysis via Dynamical Systems (LFADS):** това е специфичен тип автоенкодър, базиран на рекурентни невронни мрежи (Recurrent Neural Networks), който извлича динамиката на невронната активност от данни за единични неврони. [20,21]

III. Моделиране на мозъчна анатомия и физиология

Различни критерии могат да се използват за категоризиране на ЦБ. Според метода за създаване могат да бъдат ръчно, автоматично или хибридно създадени; според точността – прецизни и частично прецизни; според потока от данни – едно- и двупосочни. Цифровите близнаци на мозъка могат да бъдат структурни, интерактивни и прогностични. Структурните моделират конектома (шаблона на свързаност на невроните) и често съдържат визуализации; интерактивните могат да симулират физиологични процеси като рефлектират статистически корелации между активни области; прогностичните могат да предвиждат ефекта от външни въздействия като лекарства, травми и др.

Структурните модели на мозъка могат да се изграждат на ниво симулация на малки биологични невронни мрежи за тестване на сигнали (например при хирургично планиране на импланти) или тестване на нови изследователски модели; може да се моделират конектоми чрез графови структури, които описват шаблони на свързване в контекста на техните поведенчески корелати; може да се обвържат с визуални симулации във виртуална реалност (ВР) с цел подпомагане на образованието или симулирани операции при предоперативна подготовка. Класически среди за разработка на

виртуална реалност като Unreal Engine и Unity могат да се използват за създаване на добри визуални модели.

Използването на ВР за създаване на виртуални близнаци на мозъка допринася за холистичния подход към цифровизацията на медицината. Предимства на интеграцията на визуален триизмерен модел към цифров близнак са лесното мащабиране на мозъчния модел (zoom), частично рендериране в синхрон с фокуса на потребителя на модела и триизмерно разслояване, което позволява поглед в дълбочинната структура на мозъка. Чрез ВР могат да се създадат не само статични визуални, но и динамични интерактивни модели на мозъка чрез инкорпориране на данни от образни технологии, като може дори да се добави озвучаване (сонификация), обвързано със симулирани мозъчни дейности. Разработчиците трябва да прилагат редукция на броя на полигоните при запазване на геометричната форма на визуалните модели и да преобразуват текстурите в компресирани формати. Триизмерни ВР модели могат да се съхраняват в различни файлови формати [22-25].

Формат	**Приложение**	**Ключова характеристика**
glTF / GLB	WebXR, VR очила	Бързо зареждане в уеб среда
FBX	Unity, Unreal Engine	Поддържа анимации и скелети
OBJ	Статични 3D модели	Само геометрия и UV координати
GIFTI (.gii)	Невронауки	Визуализация на мозъчни повърхности
NIfTI (.nii)	Невроизобразяване	Съхранява 3D обемни данни (воксели)
HDF5	Научни данни	Ефективно управление на големи масиви
USD / USDZ	Apple visionOS, сложни сцени	Поддържа слоеве и комплексни 3D сцени

Таблица 1*. Файлови формати за ВР модели [22-25]*

В допълнение към ВР моделите, може да се изгради уеб система за улесняванена публичния достъп до изградения модел. Уеб визуализациите на ВР модели разчитат на платформите WebXR – отворен стандарт за браузъри, който позволява директна визуализация без допълнителни приложения. За изграждане на триизмерни уеб визуализации се използват следните платформи:

- **Three.js** е JavaScript библиотека, върху която е изградена A-Frame. Работи с WebGL/WebGPU и осигурява прецизен

контрол върху текстури, буфери и шейдъри. Подходяща е за визуализация на фиброва трактография и поддържа InstancedMesh, позволяващ изобразяване на десетки хиляди неврони. [26]

- **A-Frame** е базирана на Three.js и използва архитектура „Entity-Component-System“ (ECS), подобна на HTML. Позволява изграждане на VR среди чрез стандартни HTML елементи и е подходяща за образователни уеб приложения. Поддържа едновременен достъп на множество потребители чрез WebRTC. [26]
- **Babylon.js**, разработвана с подкрепата на Microsoft, представлява пълнофункционална платформа за 3D и BP приложения. Подходяща е за биофизични симулации, като включва физични енджини (напр. Havok), моделиране на материали и разширена хардуерна интеграция. [27]
- **Regl** е специализирана WebGL библиотека, която предоставя директен декларативен интерфейс към графичния процесор, без използване на сценичен граф. Благодарение на високата си производителност е подходяща за визуализация на мащабни конектомни данни. [28]

Освен във файлове мозъчни дни се съхраняват и в специализирани бази от данни. Графична база данни на EBRAINS е основната архитектура на европейската изследователска инфраструктура [29]. EBRAINS използва графична база данни за свързване на разнородни набори от данни в областта на невронауките, изчислителни модели и софтуер от различни области. Тя използва openMINDS (open Metadata Initiative for Neuroscience Data Structures) – модел за метаданни за свързани данни, създаден специално като архитектурен проект за графични бази данни в невронауките.

Мозъчната активност се проявява чрез електрически, магнитни и хемодинамични сигнали, които могат да бъдат регистрирани със специализирани технологии. Инвазивните методи изискват имплантиране на електронни устройства в директен контакт с невроните и се прилагат основно при тежки неврологични състояния. Примери са кохлеарните импланти, дълбоката мозъчна стимулация, ретиналните импланти и мостовите невронни протези. Неинвазивните методи използват външни устройства за директно или косвено измерване на мозъчната активност, включително чрез електроокулография и

електромиография [30]. Електроенцефалографията (ЕЕГ) регистрира електрическата активност на мозъка чрез електроди върху скалпа. Тя се отличава с висока времева разделителна способност, ниска цена и лесна употреба, но има ограничена пространствена точност и е чувствителна към шум [31-39]. Функционалната близка инфрачервена спектроскопия (fNIRS) оценява мозъчната активност чрез промени в окислението на кръвта и намира приложение в научни изследвания, клинична диагностика и неврорехабилитация [40, 41]. Функционалният магнитен резонанс (фЯМР) използва BOLD сигнала като индикатор за локални промени в кръвообращението, свързани с мозъчната активност. Недостатъците му са високата цена и необходимостта от специализирана инфраструктура [42-46]. Дифузионно-тензорното изобразяване (ДТИ) е разновидност на ЯМР, която визуализира структурните връзки в бялото вещество на мозъка чрез проследяване на дифузията на водните молекули. Магнитоенцефалографията (МЕГ) измерва магнитните полета, породени от мозъчната активност, но изисква скъпо оборудване [47]. Сред изброените технологии ЕЕГ е най-достъпна по отношение на цена и удобство, като съществуват и потребителски устройства за домашна употреба. Всички методи могат да генерират данни за мозъчна активност, свързана с определени стимули. Анализът на тези данни позволява моделиране на зависимостите между стимули и реакции и може да служи като основа за изграждане на ЦБ.

ГИИ може да се използва за генериране на симулирани данни от ЕЕГ/МЕГ/фЯМР/ДТИ за мозъчна активност или за генериране на модели на биологични невронни мрежи. За обучението на ГИИ са необходими надеждни набори от данни. Neurosynth е база данни с 14371 мозъчни изследвания [48]. OpenFMRI съдържа набори от фЯМР записи на хора, извършващи различни задачи [49]. OpenNeuro е платформа за споделяне на данни за мозъчна активност [50]. На сайта могат да се намерят набори от данни от различни изследвания – COMSOL, LONI, IBSR, OASIS, ITK, ImageJ, MIPAV, OSIRIX, Sage, Shogun. Архивите на PhysioNet [51], свързани с мозъка, включват солидна колекция от набори от данни за електроенцефалограма и полисомнография, като например базите данни CHB-MIT Scalp EEG и Sleep-EDF. Тези ресурси предлагат многоканални записи с висока резолюция, анотирани от експерти за събития и етапи на съня, подпомагащи изучаването на епилепсия,

нарушения на съня и когнитивно здраве. На сайта [52] е наличен списък с набори от ЕЕГ записи на различни типове мозъчни електрически потенциали – ErrP, SSVEP, VEP, SCP и др. В добавка може да се интегрират традиционните софтуери за невронно моделиране, например софтуер за симулация на т. нар. Пробивни невронни мрежи (Spiking neural networks). Съществува разнообразие от софтуер за създаване на симулации на биологични невронни мрежи.

Извън чистия ИИ, цифровите близнаци на мозъка често разчитат и на математически уравнения, които описват мозъчната физиология. Някои подходи са Neural Mass Models (описват средната активност на големи популации от неврони [53]), Dynamic Causal Modelling [54] (за оценка на това как една мозъчна зона влияе на друга (ефективна свързаност), The Virtual Brain **(**отворена платформа, която интегрира структурни данни от ЯМР с математически модели на невронна динамика [55]).

Тестването на виртуални лекарства включва модели на клетки, фармакокинетично и фармакодинамично моделиране (PBPK/PD) [56], мрежова активност и виртуални популации. Компартментното моделиране разглежда тъканите като отделни резервоари, докато физиологично базираната фармакокинетика (PBPK) използва параметри като органен обем и тъканна пропускливост. Прилагат се и математически и статистически методи, включително Non-linear Mixed Effects Modeling. Генната регулаторна мрежа (Gene Regulatory Network – GRN) представлява система от ДНК, РНК и протеини, които контролират генната експресия в клетките и тъканите [57]. За моделиране на GRN се използват алгоритми като GENIE3, SIRENE, GRADIS, DeepSEM, RSNet, GCLink и DeepMCL [58, 59]. Те прилагат техники за МО, включително дървета на решенията, графови и циклични невронни мрежи, векторни машини и автоенкодъри. Генната експресия е свързана с поведението на невроните и формирането на синаптични връзки [59]. Интегрирането на тези мрежи в ЦБ на мозъка позволява холистичен анализ на мозъчните процеси.

IV. Практическа реализация на генеративни методи с мозъчни данни

Данните за мозъчна дейност изискват предварителна обработка. Мозъчната дейност често съдържа значително

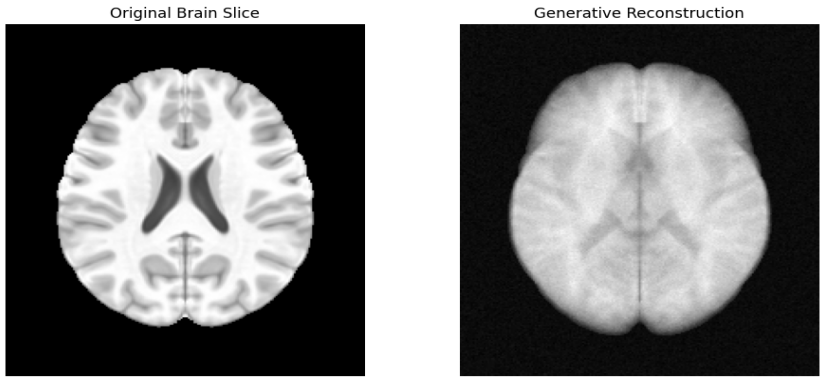
количество шум и артефакти, които трябва да бъдат почистени. За целта могат да се използват техники от МО като анализ на независими компоненти (Independent Component Analysis), групиране, анализ на главни компоненти (Principal Component Analysis) и др. След прилагане на съответните алгоритми обикновено е необходима пряка човешка намеса за идентификация на отклонения от целевата мозъчна дейност, на базата на знания за функционалната структура на мозъка. Предложени са множество поточни линии за стандартизирана обработка на определени категории данни за мозъчна активност. Библиотеката MNE [60] е популярна за обработка на данни за мозъчна активност. Съдържа инструменти за визуализация, права и обратна задача за картографиране на активност, алгоритми за обработка и разделяне на сигнали.

При избор на модели за МО трябва да се вземат предвид няколко съображения:

- **Избор на невронни активационни функции**: активационните функции имат ограничени обхвати от стойности, което е ключов критерий за подбор спрямо наличните данни. Например, функции като хиперболичен тангенс и логистичната функция са ограничени в интервали (-1,1) и (0,1) съответно, а функцията ReLU е в интервала (0,∞). Дори реалните данни да не се побират в обхватите на активационните функции, е възможно да се приложи преформатиране (например на мерни единици) или нормализация на данните.
- **Архитектура на невронните мрежи**: практиката показва, че дълбоки архитектури постигат по-висока точност на възпроизвеждане на данните, но твърде сложни архитектури могат да доведат до претрениране (overfitting). Оптимизирането на архитектурите може да се извърши чрез методи като Network Architecture Search, Drop-out, регуляризация и др.
- **Налични изчислителни ресурси:** различни инструменти за МО изискват различна изчислителна мощ, освен това данните заемат различен обем памет. Изборът на данни и модели трябва да е съобразен с параметрите на всеки експеримент.

```
img = datasets.load_mni152_template()
data = img.get_fdata()
# Training Data preperation - slicing
n_slices = data.shape[2]
slices = []
for i in range(n_slices):
    slices.append(data[:, :, i].flatten())
X = np.array(slices)
scaler = MinMaxScaler()
X_scaled = scaler.fit_transform(X)
# Autoencoder using MLPRegressor
autoencoder = MLPRegressor(hidden_layer_sizes=(100,),
activation='relu', solver='adam', max_iter=200, ran-
dom state=42)
```

Фиг.1. а) горе *фрагмент от кода за експеримента* ***б) долу*** *сравнение между оригинални данни и симулирани от кода*



Python е програмен език, който в последните години се превърна в де факто стандарт за МО. Популярни библиотеки са scikit-learn [61], TensorFlow [62] и PyTorch [63]. Scikit-learn е насочена към широк набор модели за МО, съдържа множество допълнителни инструменти за обработка на данни, но не е оптимизирана относно бързина и производителност. От друга страна TensorFlow е по-тясно специализирана в дълбокото обучение и е налична оптимизация за работа с графични и тензорни процесори. На Фиг. 1 а) е представен фрагмент от Python код за провеждане на малък експеримент за обучение на автоенкодър с мозъчни данни от ЯМР. Използван е моделът MLPRegressor от библиотеката scikit-learn с ReLU активация. Данните са нарези от триизмерен модел на мозък от набора, наличен в библиотеката nibabel [64] [65].

На Фиг.1 б) е показано сравнение между оригинално парче данни и възстановка чрез автоенкодъра. Данните са предварително мащабирани, което влияе на визуалното качество, но въпреки това се вижда, че е запазена структурата на сканирания отрез.

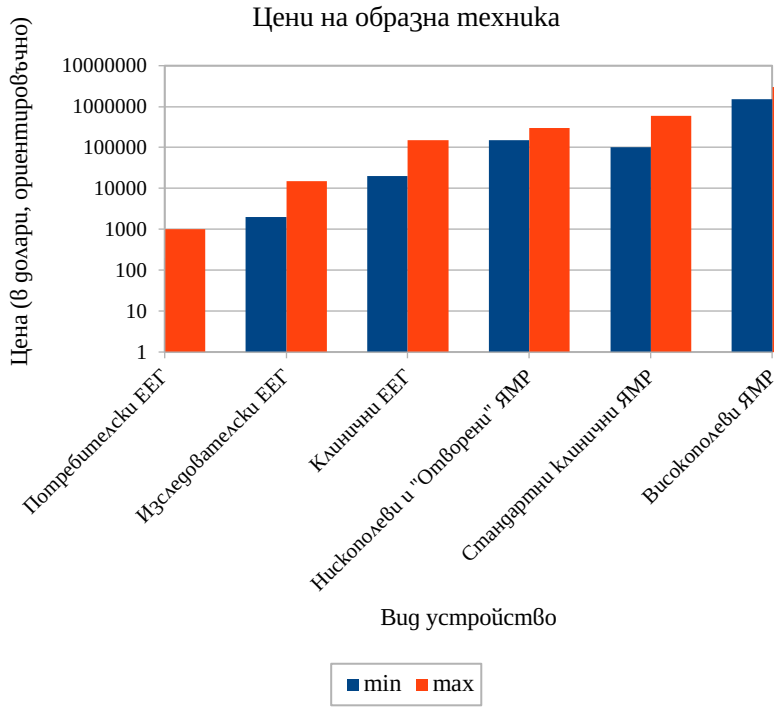
IV. Финансови аспекти на цифровите близнаци в медицината

Използването на ЦБ е ключов подход за намаляване на цената на медицинските изследвания. В тази секция е направен кратък обзор на ориентировъчните разходи, на базата на който може да се направят приблизителни обобщения за икономически ефекти.

Мозъчните изследвания могат да се класифицират като клинични и изследователски. Медицинските разходи са свързани с характера на болничните заведения (частни, публични), държавни политики (субсидиране и др.). Изследователските разходи са свързани с програми и грантове за научна дейност. Разходите за мозъчни изследвания могат да се класифицират като разходи за изграждане (Capital Expenditure - CAPEX) и оперативни разходи (Operating Expenditure – OPEX). Включват разходи за апарати, помещения, обучение на персонал, лицензиране**.**

От CAPEX категорията разходите за апаратура са компонентът с най-голяма тежест в общия разходен микс. Разходите за обучение на медицински персонал също са значителни. Медицината е сред най-скъпите образователни направления, независимо дали обучението се финансира от студентите или чрез публични програми [66]. Съществуват съществени различия между държавите – през 2019 г. разходите за обучение на студент по медицина се оценяват на около €228 000 годишно в САЩ, €39 000 в Австралия и €53 300 в Иран [66]. Значителна част от тези разходи са свързани с изграждането и поддръжката на специализирана инфраструктура. ЕЕГ устройствата са от ниския ценови клас [67,68], а инвестицията в ЯМР е една от най-големите в медицинската практика [69]. МЕГ установките са друга технология с висока цена [70]. На Фиг.2 е направено ценово сравнение на технологиите. Достъпът до виртуални органи създава условия за провеждане на практически занятия и в дистанционна форма, което повишава гъвкавостта на образователните програми и разширява достъпа до тях. Едновременният достъп на много обучаеми до една и съща

виртуална среда съкращава времето за практики и осигурява добра мащабируемост без съществено увеличение на разходите.



Фиг. 2. *Ориентировъчни цени на устройства за мозъчно сканиране*

Цените на графиката са ориентировъчни и актуални към периода март-май 2026 г., взети от търговски сайтове: [67-74] и други.

Друго значимо перо са разходите за помещения. ЕЕГ кабинетът не изисква огромни инвестиции, но се нуждае от добра звукоизолация и електрическа тишина. Необходимата площ е 12-15 кв.м., със заземяване. Разходите за помещение за ЯМР са мащабни, тъй като помещението трябва да изолира околния свят от магнитното поле и обратното. В таблица 2 са обобщени разходите за отделни компоненти на ЯМР установката. Помещения за МЕГ обикновено изискват инвестиция от порядъка на 3 милиона долара, която включва SQUID сензори, екраниране и изолация на помещенията, инсталация за охлаждане с течен хелий и др. [70, 71, 72] Анализ на пазара на fNIRS може да се види тук [73].

Компонент	Приблизителна цена (€)	Описание
Фарадеева клетка (RF Shielding)	15000 – 70000	Специална облицовка на стените, пода и тавана, за да се блокират радиочестотни смущения.
Укрепване на пода	5000 – 15000	Един ЯМР тежи между 4 и 7 тона.
Магнитна изолация (Pas-sive Shielding)	10000 – 30000	Ако наблизо има асансьори или паркинг, се изисква стоманена изолация
Климатизация и Чилър (Chiller)	15000 – 42000	ЯМР се нуждае от прецизен контрол на температурата
Quench тръба (Вентилация)	3000 – 7000	Система за аварийно извеждане на хелия извън сградата при инцидент.

Таблица 2. *Ориентировъчни разходи за помещения за ЯМР*

OPEX включват разходи за консумативи, електроенергия, амортизация, заплати на персонала. Цената на сесия за получаване на мозъчни данни варира според цената на консумативи и заплащане за труд. Една сесия за запис на ЕЕГ данни е обичайно от порядъка на €45 – €90, в зависимост от продължителността, като по-дългосрочен мониторинг на съня може да достигне до €600. Оперативната цена на ЯМР сесиите е висока, стандартно изследване на една зона (глава, гръбнак) започва от около €180-€300 в Източна Европа и достига до €500-€600 в Западна Европа. Изследване с контраст добавя €50-€100. Цената на МЕГ сесиите е чувствително по-голяма, като стига порядък от €500 на час. По тази причина МЕГ установките в целия свят са много малък брой. Анализът на данни с цел подготовка за научни изследвания допълнително оскъпява конкретни сесии. Всички изброени ценови бариери затрудняват изследванията и натоварват образователните институции. Основната полза от ЦБ е, че позволяват генерирането на изкуствени данни с добро качество, без да налагат разходи за амортизация и поддръжка на апаратура. Освен това ЦБ са защитени спрямо физически инциденти с апаратурата, като позволяват и съществуването на резервни копия.

При ЕЕГ са налице следните консумативи - гелове и пасти за намаляване на импеданса между кожата и електрода; електроди и аксесоари, като цената тук зависи силно от материала – злато, сребро /сребърен хлорид; допълнителни материали са медицински пластири, почистващи тампони с алкохол, спринцовки, но тези разходи за от порядъка на центове и обикновено са пренебрежими. При ЯМР се използва течен хелий **(**цена: €25 – €50 на литър при изисквания между 1500 и 2000 литра за първоначално пълнене и дозареждане); контрастни вещества (цена: €40 – €100 на доза за един пациент); еднократни материали за пациента - слушалки, предпазни калъфи, хигиенни подложки (цена около €2 – €5 на пациент); разходи за електричество (месечната сметка за ток на един ЯМР апарат може да варира между €1500 и €3000, тъй като охлаждащите системи работят денонощно).

Използването на ЦБ, които генерират изкуствени данни за ЯМР или МЕГ може да спести голяма част от изброените разходи, но от своя страна също изисква разходи за изчислителна техника, електрическа консумация и заплати на специалисти. Общият размер на разходите зависи от мащаба на проекта за цифров близнак. Изчислителните машини са лесно заменями, което намаля цената за поддръжка и ремонт спрямо медицинската апаратура.

V. Дискусия

In-silico опити в изследователски проекти могат да намалят разходите за заплащане на доброволци за контролни групи, което намалява и технологичното време на експериментите. Компании като *Unlearn.AI* вече демонстрират възможност за намаляване на размера на контролните групи с 30% [75], което спестява много пари при разработка на лекарства за Алцхаймер или епилепсия. В клиничен контекст пробните виртуални операции могат да намалят риска от усложнения и да намалят вероятността за повторна коригираща операция. Виртуални скенери могат също да предвидят повреди в реалната апаратура и да спестят разходи по ремонти. Разходите за изграждане на ЦБ включват разходи за намиране, съхранение и обработка на данни (например осигуряване на HIPAA/GDPR съвместимост [76]), разходи за изчислителна мощ при обучението на моделите, потенциални разходи за използване на лицензиран софтуер и разходи за човешки ресурс. Допълнително регулаторната съвместимост може да увеличи разходите поради изисквания за обемни симулации и

институционално тестване. Подходи като DePIN могат да намалят изчислителните разходи чрез децентрализирано управление на хардуера. Въпреки цената на първоначалната инвестиция за създаване на ЦБ, Return Of Investment се реализира в кратък срок и имплементацията променя изследователския модел от реактивен към предсказващ.

Сред техническите недостатъци на ЦБ са високата цена за създаване и наследената неяснота на имитирани биологични модели, както и рискове относно нерегламентиран достъп до чувствителна информация. В много случаи на клиничната практика са налице данни за корелация между симптоми и заболявания, които обаче не разкриват прецизно характера на връзката. Самите модели за ИИ като невронните мрежи са също „черни кутии“ - тяхната сложност не позволява смислена интерпретация от човек. По този начин неяснотата на процесите за запазва. Проблемът надхвърля медицинската употреба на ИИ и може да се адресира чрез методи за обясним ИИ (eXplainable AI - XAI).

Направеният обзор илюстрира възможностите на моделите с ИИ да симулират мозъчна дейност и предоставя качествена оценка на потенциалните ползи от внедряването им в клиничната и изследователската практика.

Литература:

1. Laubenbacher, R, Mehrad, B, Shmulevich, I, Trayanova, N. Digital twins in medicine. Nature computational science. 2024
2. Zhang, K., Zhou, H., Baptista-Hon, D., Gao, Y., Liu, X., Oermann, et al., Concepts and applications of digital twins in healthcare and medicine. Patterns. 2024
3. Björnsson, B., Borrebaeck, C., Elander, N., Gasslander, T., Gawel, D. et al. Digital twins to personalize medicine. Genome medicine. 2019
4. Braun, M.. Represent me: please! Towards an ethics of digital twins in medicine. Journal of Medical Ethics. 2021
5. Sadée, C., Testa, S., Barba, T., Hartmann, K., Schuessler et al., Medical digital twins: enabling precision medicine and medical artificial intelligence. The Lancet Digital Health. 2025
6. Bruynseels, K., Santoni de Sio, F., Van den Hoven, J. Digital twins in health care: ethical implications of an emerging engineering paradigm. Frontiers in genetics. 2018
7. Marchal I. Applications of digital twins in medicine. nature biotechnology. 2025

8. Ghatti S, Yurish LA, Shen H, Rheuban K, Enfield KB, Facteau NR et al., Digital twins in healthcare: A survey of current methods. Arch. Clin. Biomed. Res. 2023
9. Bachmann, JE, Silveira, IF, Martins, VF., Digital twins for education: A literature review. Simpósio Brasileiro de Informática na Educação (SBIE). 2024
10. Yang W, Shen S, Yang D, Yu S, Yao Z, Cao S. Digital twin applications in medical education: A scoping review. Education Science and Management. 2024
11. Ezeoguine PE, Kasumu RY. Undergraduate students' perception of digital twins technology in education: uses and challenges. Int. J. Educ. Eval. 2024
12. Zhao, T., Cui, Y., Ji, T., Luo, J., Li, W., et al,, VAEEG: Variational auto-encoder for extracting EEG representation. NeuroImage. 2024
13. Chien, H., Goh, H, Sandino, C., Cheng, J.. Maeeg: Masked auto-encoder for eeg representation learning. arXiv preprint arXiv:2211.02625. 2022
14. Tian, C., Ma, Y., Cammon, J., Fang, F., Zhang, Y., Meng, M. Dual-encoder VAE-GAN with spatiotemporal features for emotional EEG data augmentation. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2023
15. Abibullaev, B, Keutayeva, A, Zollanvari, A,. Deep learning in EEG-based BCIs: A comprehensive review of transformer models, advantages, challenges, and applications. IEEe Access. 2023
16. Song, K., Zhou, L, Wang, H., Deep coupling recurrent auto-encoder with multi-modal EEG and EOG for vigilance estimation. Entropy. 2021
17. Chehab, O., Défossez A, Jean-Christophe L, Gramfort A, King JR. Deep Recurrent Encoder: an end-to-end network to model magnetoencephalography at scale. Neurons, Behavior, Data Analysis, and Theory. 2022
18. Wei R, Mahmood A. Recent advances in variational autoencoders with representation learning for biomedical informatics: A survey. Ieee Access. 2020
19. Sikka H, Zhong W, Yin J, Pehlevant C. A Closer Look at Disentangling in β-VAE. In2019 53rd Asilomar conference on signals, systems, and computers 2019
20. Huang, J, Tostado-Marcos, P, Narasimha, SM, Patel, AN, Arneodo, EM et al. V. Guiding Brain-to-Vocalization Decoder Design Using Structured Generalization Error. In2024 46th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) 2024
21. Ye J, Pandarinath C. Representation learning for neural population activity with neural data transformers. arXiv preprint arXiv:2108.01210. 2021
22. https://www.meshy.ai/blog/3d-file-formats
23. https://balsa.wustl.edu/about/fileTypes
24. https://www.brainvoyager.com/bv/doc/UsersGuide/CoordsAndTransforms/ProcessingNIfTIFiles.html
25. https://www.hdfgroup.org/
26. https://aframe.io/docs/1.7.0/introduction/developing-with-threejs.html
27. https://www.babylonjs.com/

28. https://regl-project.github.io/
29. https://ebrains.eu/data-tools-services/data-knowledge/find-data
30. Jeong, S, Lee, S, Koh, J, An, H, cheol Jeong, I. Eye Image and EOG Signal Conversion via Autoencoders for Human-Machine Interaction. 2025 IEEE International Conference on Consumer Electronics (ICCE) 2025
31. Qiu L, Feng W, Zhong L, Song X, Ying Z, Pan J. Mutual information learning-based end-to-end fusion network for hybrid EEG-fNIRS brain-computer interface. IEEE Transactions on Instrumentation and Measurement. 2025
32. Song Y, Liu B, Li X, Shi N, Wang Y, Gao X. Decoding natural images from eeg for object recognition. arXiv preprint arXiv:2308.13234. 2023
33. Lai, J., Wei, J., Yao, L., Wang, Y. A simple review of eeg foundation models: Datasets, advancements and future perspectives. arXiv preprint arXiv:2504.20069. 2025
34. Bai, Y., Wang, X., Cao, Y,, Ge. Y,, Yuan. C,, Shan. Y. Dreamdiffusion: Generating high-quality images from brain eeg signals. arXiv preprint arXiv:2306.16934. 2023
35. Duan Y, Zhou J, Wang Z, Wang YK, Lin CT. Dewave: Discrete encoding of eeg waves for eeg to text translation. Advances in Neural Information Processing Systems. 2023
36. Jain, S., Srivastava, R.. Multi-modality NDE fusion using encoder–decoder networks for identify multiple neurological disorders from EEG signals. Technology and Health Care. 2025
37. Jiao, Y., Zhang, Y., Zhang, J.. CNN-Transformer Based Real-Time Detection of Driver Sleep Onset Using EEG and EOG Signals. IEEE International Conference on Bioinformatics and Biomedicine (BIBM) 2025
38. Cui. W,, Jeong, W., Thölke, P., Medani, T., Jerbi, K., Joshi, A., Leahy, R. Neuro-gpt: Towards a foundation model for eeg. In2024 IEEE International Symposium on Biomedical Imaging (ISBI) 2024
39. Yan, B., Wang, Y., Li, Y., Gong, Y., Guan, L., Yu, S. An EEG signal classification method based on sparse auto-encoders and support vector machine. In2016 IEEE/CIC International Conference on Communications in China (ICCC) 2016
40. Sirpal, P., Damseh, R., Peng, K., Nguyen, D., Lesage, F.. Multimodal autoencoder predicts fNIRS resting state from EEG signals. Neuroinformatics. 2022
41. Guglielmini, S., Banchieri, V., Scholkmann, F., Wolf. M., Transformer-based deep learning model for predicting fNIRS short-channel signals. Neurophotonics. 2025
42. Han K, Wen H, Shi J, Lu KH, Zhang Y, Fu D, Liu Z. Variational autoencoder: An unsupervised model for encoding and decoding fMRI activity in visual cortex. NeuroImage. 2019
43. Liu P, Dong G, Guo D, Li K, Li F, et al.,. A survey on fmri-based brain decoding for reconstructing multimodal stimuli. arXiv preprint arXiv:2503.15978. 2025

44. Beliy, R., Gaziv, G., Hoogi, A., Strappini, F., et al., From voxels to pixels and back: Self-supervision in natural-image reconstruction from fmri. Advances in Neural Information Processing Systems. 2019
45. Lu H, Liu S, Wei H, Tu J. Multi-kernel fuzzy clustering based on auto-encoder for fMRI functional network. Expert Systems with Applications. 2020
46. Oota, S., Rowtula, V, Gupta, M., Bapi, R. StepEncog: A convolutional LSTM autoencoder for near-perfect fMRI encoding. 2019 International Joint Conference on Neural Networks (IJCNN) 2019
47. Miyazaki, K., Nirasawa, S., et al., Suppression of information spreading in *MEG* source estimation using a functionally-structured Bayesian approach, 2026
48. https://neurosynth.org/studies/
49. https://openfmri.org/dataset/
50. https://openneuro.org/
51. https://www.physionet.org/about/database/
52. https://openbci.com/community/publicly-available-eeg-datasets/
53. Francesca Castaldo, Raul de Palma Aristides, Pau Clusella, Jordi Garcia-Ojalvo, Giulio Ruffini, Rosetta stone of neural mass models, Physics Reports, Volume 1189, 2026
54. [54] Yuan, W., Yao, W., Yvonne, W.. L, Generalized Recurrent Neural Network accommodating Dynamic Causal Modeling for functional MRI analysis, NeuroImage, Volume 178, 2018
55. https://www.thevirtualbrain.org/tvb/zwei/
56. Talkington, A., Cao, Y., et al.,, Opportunities for machine learning and artificial intelligence in physiologically-based pharmacokinetic (PBPK) modeling, Advanced Drug Delivery Reviews, Vol. 227, 2025
57. Sinha,B., Jones, I., Traniello, S. et al., Behavior-related gene regulatory networks: A new level of organization in the brain, Proc. Natl. Acad. Sci. U.S.A. 117 (38) 23270-23279
58. [grn] Wang, Y.,, Li L, Li JJ, Huang H. Network Modeling in Biology: Statistical Methods for Gene and Brain Networks. Stat Sci. 2021
59. Hegde, A., Nguyen, T., Cheng, J., Machine learning methods for gene regulatory network inference, Briefings in Bioinformatics, Vol. 26, Issue 5, 2025
60. https://mne.tools/stable/index.html
61. https://scikit-learn.org/stable/
62. https://www.tensorflow.org/
63. https://pytorch.org/
64. https://peerherholz.github.io/workshop_weizmann/data/image_manipulation_nibabel.html
65. https://github.com/Jfortin1/MNITemplate
66. Hashjin, A., Irandoust, K., Gholampoor, H. et al., Comparing Medical Training Costs Internationally: A Systematic Review. Med J Islam Repub Iran. 2024

67. https://mfimedical.com/products/nihon-kohden-neurofax-eeg-9100-portable-eeg-machine?srsltid=AfmBOopssPNMh_stHbiwOAbJlzabwem-WGiACbs7hezxc4gs_MgLkZJ2c
68. https://bimedis.com/catalog/natus-neurology-equipment-eeg-systems-6547-988
69. https://bimedis.com/catalog/siemens-magnetic-resonance-imaging-mri-machines-5526-494
70. https://www.coherentmarketinsights.com/market-insight/magnetoencephalography-market-2467
71. https://brainbox-neuro.com/products/mag4health-he-opm-meg-system
72. https://www.coherentmarketinsights.com/market-insight/magnetoencephalography-market-2467
73. https://www.cognitivemarketresearch.com/fnirs-brain-imaging-system-market-report
74. https://newsroom.technavio.org/neurology-devices-market-analysis
75. https://www.unlearn.ai/digital-twins
76. https://www.hhs.gov/hipaa/index.html

МЕКИТЕ УМЕНИЯ КАТО ПЕДАГОГИЧЕСКА НУЖДА ЗА УСПЕШНОТО ИЗПЪЛНЕНИЕ НА СЧЕТОВОДНАТА ФУНКЦИЯ

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SOFT SKILLS AS A PEDAGOGICAL NECESSITY FOR THE EFFECTIVE PERFORMANCE OF THE ACCOUNTING FUNCTION

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Abstract: *The necessity of soft skills in higher education to do with accounting management is an identified reality (Анкова-Стоянова, 2020). Following Evers et al's landmark paper (1998), which explores the problem of soft skills in the context of higher education, the workplace, and the transition between the two, there have been a multitude of investigations on this problematic in a wide range of international contexts and varying scales. In order to take seriously the context of Industry 4.0, it is important to note that the accounting function in a given company is undergoing significant changes, and it needs to overcome novel challenges. In this context, there is a need to review the current pedagogical literature, as well as existing data regarding current educational programmes, to do with this problem.*

Keywords: *Soft skills; Accounting education; Higher education; Industry 4.0*

Въведение

Меките умения са многопластово понятие, което трябва да бъде разглеждано като различно, но обвързано с когнитивните такива. В сърцевината на меките умения могат да бъдат открити емоционални, социални, и некогнитивни (или метакогнитивни) умения. Само по себе си, понятието индикира комплекс от способности. В конкретен план, най-често бива свързано с уменията за управлението на себе си, особено в междуличностно

отношение. В глобален план, меките умения са основата върху която други, твърди или не, умения и капацитети могат да бъдат прилагани успешно. Evers et al (1998) индикират нуждата от комплексно разбиране на меките умения в контекста на висшето образование. В този смисъл, меките умения са както способност така и основа за развитие. Връзката им с педагогиката и развитието, както и устойчивостта, на която и да е професия е явна.

Предизвикателства пред счетоводното образование

Невъзможно е да се игнорира контекста на Индустрия 4.0, обвързана с навлизането на глобални дигитални технологии, които коренно променят работния пазар и работните дейности (Станчева-Тодорова, 2022). Също така, не трябва да бъдат пренебрегвани и дългосрочните последствия от пандемията COVID-19 (Tsiligiris and Bowyer, 2021: 627). В този контекст, Garcia и de Los Rios (2021) посочват централната роля на счетоводството що се отнася до финансовата прозрачност, отговорност и надеждност. Тази роля се оказва все по-трудна именно поради постоянните промени в работната среда и функция. Ghani et al (2024) твърдят, че счетоводната професия е в особено уязвима позиция. Obembe (2025) разглежда тази ситуация като възможност за развиването на новаторски и стратегически аспекти на счетоводната функция. Tsiligiris and Bowyer (2021) индикират възможните съкращения в много сектори, както и във връзка със счетоводната функция, а и понижаване на трудовата заетост в цялостен план (2021:624; също, вж. Ghani et al, 2024), както и повишаване на изискванията за наемане на новопостъпващи. От значение тук е контекста на слаба подготовка за новодипломирали се в междуличностен план и общи професионални умения, за сметка на силната подготовка в техничен план. Kurnia and Hapsari (2025) добавят че в много отношения тези технически умения са свързани с техническо знание, не задължително с дигитални технологии (118). Tavares et al (2023) посочват напредъка на ИИ като фактор за новоустановената Индустрия 5.0, както и отбелязват по-належащата от всякога необходимост за промотиране на развитието на вътрешноличностни и междуличностни умения (2023:7). Тези предизвикателства и промени се изразяват и в педагогическата практика. А именно, как дигиталната технология

да бъде интегрирана в образованието, както и подобаващото развитие на меките умения спрямо глобалните промени и променливата работна среда. Ключов фактор е разминаването между идентифицираните нужди от конкретни умения за професията (Elo et al, 2024): в първо измерение, от страна на образователната система, на работодателя, и на постъпващия в счетоводната професия (Dolce et al, 2020); във второ измерение, стои въпроса къде, и от кого, трябва да бъде разрешено това разминаване (Succi and Canovi, 2019). Asonitou (2022) отбелязва и широкоразпространения възглед между студентите, че проекти които развиват меките умения са свободно избираеми и следователно могат да бъдат игнорирани или подценявани. Ghani et al (2024) цитират проучвания, като Tan and Laswad (2018), Succi and Canovi (2019), и Bridgstock and Jackson (2019), които твърдят че работодателите са склонни да имат по-високи очаквания към новопостъпващите в професията. В множество контексти се отбелязва очакването новопостъпващите в професията да са социално ориентирани (Tan and Laswad, 2018), както и да са способни да комуникират ефективно и да работят в екип (Carvalho and Almeida, 2022; Ghani et al, 2024). Belkbir пояснява (2018) че положението е същото и в инженерната професия, при която новодипломирали се често биват смятани за неподготвени в професионално и социално отношение, т.е. що се отнася до меки умения. В настоящия си труд, Ghani et al (2024:10) посочват инверсията на тази картина при новозавършилите счетоводители—откритията им явно заявяват, че преподавателите успешно са отговорили на нуждите на работодателите, поне що се отнася до конкретната извадка от населението, и в момента надценяват необходимостта от множество умения спрямо заявените очаквания от страна на работодателите. Carvalho and Almeida (2022) посочват стратегическото значение на развитието на нетехнически умения от страна на висшите учебни заведения. Въпреки това, Asonitou (2022) представя изчерпателна картина на предизвикателствата пред счетоводната педагогика която цели да е актуална, в крак с промените и напълно оползотворяваща дигиталните трансформации. Asonitou изрежда следните предизвикателства пред развитието на уменията (2022:250-251): несъвместимост с професионалните ценности на преподавателите (политически или липса на желание да се преподава с цел работоспособност);

пазарната ориентация на висшето образование; множеството концептуални рамки на умения и капацитети, както и липсата на единогласие относно приложението им; конфликта между стимула за изследователски труд и преподаване; липсата на ресурси и множеството ограничения на преподавателския труд; нагласите на студентите и нивото на капацитет за учене в рамките на висшето образование; нагласите на преподавателите (напр. традиционни методи на изпитване и оценка, избягване на новаторство или страх от негативна обратна връзка); физически бариери (напр. езикови); културната спецификата на меките умения; липсата на консенсус относно педагогика и липсата на установена методика за преподаване на меки умения; ниската дигитална грамотност и липсата на ресурси в това отношение. Систематичният обзор на литературата представен от Asonitou (2022) ясно подчертава многопластовостта на предизвикателствата пред счетоводното образование в търсенето си на способна професия, която е адаптивна, гъвкава и ефикасна.

Потенциални решения

Като решение, Garcia и de Los Rios (2021; вж. Carvalho and Almeida, 2022) предлагат педагогика ориентирана към проблеми (problem-based learning, или PBL), поради начина, по който изгражда практични умения, стимулира себе-управление по време на работа върху проект, и засилва междуличностни умения въз основа на работа в групи PBL изисква усвояването на ключов технически материал, но съдържа и елемент на приложение. Именно в този аспект, прилагането на усвоения материал позволява адресирането на конкретни дефицити и нужди от страна на студентите като същевременно развива компетенциите с директна връзка към професионалното им приложение. Garcia and de Los Rios (2021:4) посочват три ключови приложения на методиката. Първо, методиката на PBL интегрира работа по проекти въз основа сътрудничество и в екипи. Второ, стажантските схеми са изключително успешни поради изискванията на контекста да се работи в професионална среда и да се прилагат реални счетоводни умения. Трето, изследователските проекти подпомагат студентите да развият професионалните си компетентности. Работата в екип или въз основа на конкретни цели подпомага цялостния процес като усвояването на нови знания и прилагането

им се извършват в среда на обратна връзка и параметри оценяващи не само знание, ами и успешно приложение. В по-широк педагогически план, Garcia and de Los Rios (2012) посочват комплексен модел въз основа на работа с 46 преподавателя от 26 международни ВУЗ и 320 студенти. Според откритията на Garcia and de Los Rios (2021:14), PBL методиката може да бъде прилагана на всеки етап от висшето образование, но е необходимо да се прилага умерено в първата година, тъй като знанието на студентите е най-ниско на този етап. Изследователите посочват третата година (в рамките на тригодишна бакалавърска степен) за най-подходящ етап, на който може да се подходи цялостно към техническата материя като се инкорпорират и възможности за развитие на: умения за преговори, организационни умения, лидерство и мотивация; както и: задаването на цели в рамките на проект; подобряване на спазването на крайни срокове и повишаване ефикасността на работа в различни етапи на проекти; така и развитието на цялостна ориентация за работа по проекти (2021:14).Kurnia and Hapsari (2025:119) предлагат паралел на този подход във формата на модел на учене чрез проект (project-based learning). Според тях, тази методика позволява практично и контекстуално учене. Това от своя страна изисква предизвикателни проекти, които са актуални—предизвикателство по своему за преподавателите. Kurnia and Hapsari отбелязват че този модел на учене е пряко обвързан с модел на педагогика, следователно изискващ от двете страни, но водещ до динамични и интерактивни сесии. Въз основа на мета-анализ на 66 публикации на тема project-based learning, Zhang and Ma (2023:8) докладват че методиката води до повишен интерес от страна на студентите в учебния процес, което потенциално може да повлияе на силното им представяне на изпити както и да подпомогне развитието на адаптивни и вътрешноличностни елементи, както и когниция. Mutanga (2024: 906-909), въз основа на интервюта с 30 студенти, докладва, че методиката на учене чрез проекти води до следните комплексни фактори, както в положителен аспект, така и потенциални трудности. А именно, необходими условия са нуждата за постоянство що се отнася до присъствие на сесии, така и трудности при адаптацията към методиката (т.е. промяна от традиционна педагогика към project-based learning), но и логистични бариери при сътрудничество; положителните страни са развитието на по-задълбочено

разбиране и практично приложение на теоретични концепции, положителните страни на сътрудничеството и работа в екип, ключовата роля на повтарящите се изпити и обратна връзка относно усвояването на понятия, цялостното насърчаване на автономия и развитието на умения за управление на времето и разрешаването на проблеми. Разгледано по този начин, комбинацията от учене чрез проблеми и чрез проекти позволява потенциалното адресиране на значителен брой препятствия идентифицирани от Asonitou (2022).

Hmelo-Silver (2004) обяснява, че PBL методиката трябва да бъде разбирана като форма на учене въз основа на опит. Allen et al (2011:23) отбелязват, че преподавателя спира да е доставчик на информация в рамката на PBL, а поема ролята на фасилитатор на ситуации в които се разрешават проблеми. Този фасилитаторски труд се състои не само в модериране на сесии и дискусии ами и в насочване на прилагането на техническо знание в групова среда с цел развитие на задълбочено разбиране на концептуални рамки и професионални стандарти. По този начин, Hmelo-Silver (2004: 236; също, вж. Nguyen et al, 2024) заявява, че методиката стимулира активното учене като поставя отговорността за процеса върху самите студенти. По-конкретно, методиката произлиза от медицинска педагогика (Allen et al, 2011) и се състои в употребата на видео материали на конкретни ситуации или създаването на изследователски проекти като опит за разрешаване на конкретен проблем (Hmelo-Silver, 2004: 237-239). Като практика, Hmelo-Silver (2004: 239) посочва ограничен набор от инструменти – списък с факти, идеи или хипотези, проблеми пред ученето и планове за действие – въз основа, на които се извежда насоченото учение чрез опит в рамките на специфичен проблем.

Ученето чрез опит най-добре бива разбрано в рамката на Kolb (1984). Kolb разграничава ученето въз основа на опит от поведенческия подход към педагогиката. По този начин, Kolb заявява че ученето трябва да бъде разглеждано като процес, а не като въпрос на резултати (1984:26). Vince (1998:305) илюстрира процеса за цикъла на учене на Kolb, а именно как може да се подпомогне ученето въз основа на конкретен опит и преживяване. Както са описани от Vince (1998:306), четирите етапа на цикъла са следните: първо, директен опит, при когото или чувства или мисли биват преживени; второ, процес на рефлекция върху преживяното; трето, извеждане на рационални заключения или емоционални

инсайти въз основа преживяването; четвърто, прилагането, пробването и инициирането на действия въз основа на преживяното.

Макар в абстрактен план, паралела с ученето чрез проблеми или проект е явно. В допълнение към Kolb, възможно е да се добави и таксономията на Bloom (1956; също така и преразгледаната таксономия, вж. Krathwohl, 2002). В първата си форма, Bloom и колеги описват 6 области на учене: знание, разбиране, прилагане, анализ, синтеза, и оценка (Krathwohl, 2002:213). Също така, на по-конкретно ниво, самото понятие „знание“ има три измерения: знание за конкретика; знание за начини и средства за работа с конкретика; и абстрактно такова.

В този смисъл, таксономията на Bloom индикира нива на абстракция които позволяват разбирането на различни типове знания, както и различни форми на техния израз. Този израз може да бъде когнитивно умение, но и такова от друг тип – напр. техническо такова, метакогнитивно или социално, т.е. меко. Именно в тази връзка, преразгледаната таксономия преименува измеренията в глаголна форма с цел наблягане на израза им в умения и способности. Необходимо е да се отбележи, че въз основа на тази класификация, може да се затвърди, че дадено умение се състои от слоеве с нарастваща сложност и приложимост като най-висшата форма се състои от способността за рефлекция върху наученото, прилагането на критерии как да се запълнят пропуски в знанието и промяна – като най-висшата форма на знание, в разбирането на Bloom (1956) и Krathwohl (2002), е именно приложението на знанието, разбрано именно в рамките на процес, в смисъла на Kolb (1984), който съдържа рефлекция, адаптация, промяна и приложение.

Заключение

Началото за адекватно посрещане на предизвикателствата в счетоводната функция в частност, в общ план Индустрия 4.0, и от цялостна гледна точка така и ефекта на второто върху първото, може да бъде открито в набора от педагогически подходи основани на опит и преживяване. Ученето чрез опит позволява интегрирането на практично ориентирани задачи на множество етапи и нива, било то чрез фокус на учене във връзка с проблем или в проект.

Според откритията на Garcia and de Los Rios (2021), ученето чрез фокус върху проблеми (или проекти, вж. Kurnia and Hapsari, 2025) може да бъде интегрирано от началото на висшето образование. От гледна точка на Kolb (1984) и Bloom (1956; също, Krathwohl, 2002), това е добра основа за цялостното интегриране на меките умения във висшето образование по счетоводство.

По-конкретно, това може да се изрази в педагогика ориентирана към усвояване на познание относно меки умения в началото на образованието, което в последствие позволява успешното приложение на меки умения в контекста на учене чрез проект или въз основа проблеми чрез методика, при която присъствието на преподавателя е основно чрез насока, подготовка на проблемите, и интегриране на възможността за приложение, както на техническо знание, така и на нетехническо такова – във формата на меки, социални и метакогнитивни умения.

Литература:

1. Allen, D. E., Donham, R. S., & Bernhardt, S. A. (2011). Problem-based learning. New directions for teaching and learning, 2011(128), 21-29.
2. Asonitou, S. (2022). Impediments and pressures to incorporate soft skills in Higher Education accounting studies. Accounting Education, 31(3), 243–272. https://doi.org/10.1080/09639284.2021.1960871
3. Belkbir, R. (2023). Engineers soft skills in the 4th industrial revolution: perspectives of employers in Morocco. International Journal of Accounting Finance Auditing Management and Economics, 4(4-2), 340-358.
4. Bridgstock, R., & Jackson, D. (2019). Strategic institutional approaches to graduate employability: navigating meanings, measurements and what really matters. Journal of Higher Education Policy and Management, 41(5), 468-484.
5. Carvalho, C., & Almeida, A. C. (2022). The adequacy of accounting education in the development of transversal skills needed to meet market demands. Sustainability, 14(10), 5755.
6. Dolce, V., Emanuel, F., Cisi, M., & Ghislieri, C. (2020). The soft skills of accounting graduates: perceptions versus expectations. Accounting Education, 29(1), 57–76. https://doi.org/10.1080/09639284.2019.1697937
7. Eames, M., Luttman, S., & Parker, S. (2018). Accelerated vs. traditional accounting education and CPA exam performance. Journal of Accounting Education, 44, 1-13.
8. Elo, T., Pätäri, S., Sjögrén, H., & Mättö, M. (2024). Transformation of skills in the accounting field: the expectation–performance gap perceived by accounting students. Accounting Education, 33(3), 237–273. https://doi.org/10.1080/09639284.2023.2191289

9. Evers, F.T., Rush, J.C. and Berdrow, I., 1998. The Bases of Competence. Skills for Lifelong Learning and Employability. Jossey-Bass Publishers.
10. García, J. L., & de los Ríos, I. (2021). Model to Develop Skills in Accounting Students for a 4.0 Industry and 2030 Agenda: From an International Perspective. Sustainability, 13(17), 9699. https://doi.org/10.3390/su13179699
11. Ghani, E. K., Ilias, A., Muhammad, K., Rosley, N. A., Mohd Ali, M., & Sukmadilaga, C. (2024). Expectation gap on accounting graduates' skill attributes between accounting educators and employers in Industry 4.0 environment: A Malaysian evidence. Educational Administration: Theory and Practice, 30(3), 1-15.
12. Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn?. Educational psychology review, 16(3), 235-266.
13. Kolb, D.A. (1984): Experiential learning: experience as the source of learning and development Englewood Cliffs, NJ: Prentice
14. Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. Theory into practice, 41(4), 212-218.
15. Kurnia, D., & Hapsari, D. P. (2025). Enhancing Pedagogical Competencies of Accounting Educators in Higher Education for the Digitalization Era. International Journal of Management Research and Economics, 3(2), 118-134.
16. Mutanga, M. B. (2024). Students' perspectives and experiences in project-based learning: A qualitative study. Trends in Higher Education, 3(4), 903-911.
17. Nguyen, L. T. V., Cleveland, D., Nguyen, C. T. M., & Joyce, C. (2024). Problem-based learning and the integration of sustainable development goals. Journal of Work-Applied Management, 16(2), 218-234.
18. Obembe, O. E. (2025). A Study of Fourth Industrial Revolution on Management Accounting Profession. Management Analytics and Social Insights, 2(2), 73-85.
19. Succi, C., & Canovi, M. (2020). Soft skills to enhance graduate employability: comparing students and employers' perceptions. Studies in Higher Education, 45(9), 1834–1847. https://doi.org/10.1080/03075079.2019.1585420
20. Tan, L. M., & Laswad, F. (2018). Professional skills required of accountants: what do job advertisements tell us? Accounting Education, 27(4), 403–432.
21. Tavares, M. C., Azevedo, G., Marques, R. P., & Bastos, M. A. (2023). Challenges of education in the accounting profession in the Era 5.0: A systematic review. Cogent Business & Management, 10(2). https://doi.org/10.1080/23311975.2023.2220198
22. Tsiligiris, V., & Bowyer, D. (2021). Exploring the impact of 4IR on skills and personal qualities for future accountants: a proposed conceptual framework for university accounting education. Accounting Education, 30(6), 621–649.
23. Vince, R. (1998). Reflections on "behind and beyond Kolb's learning cycle". Journal of Management Education, 46(6), 983-989.
24. Zhang, L., & Ma, Y. (2023). A study of the impact of project-based learning on student learning effects: A meta-analysis study. Frontiers in psychology, 14, 1202728.

ЕКСПРЕСЕН ПРАКТИЧНО ПРИЛОЖЕН ПОДХОД ПРИ ОЦЕНКА НА НЕСИМЕТРИЯТА В ЕЛЕКТРОСНАБДИТЕЛНИТЕ СИСТЕМИ НА ИНДУСТРИАЛНИТЕ ФИРМИ

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EXPRESS PRACTICALLY APPLIED APPROACH TO ASSESSING ASYMMETRY IN THE POWER SUPPLY SYSTEMS OF INDUSTRIAL COMPANIES

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Abstract: *This publication is dedicated to the possibility of express determination of electrical unbalance in the power supply systems of industrial companies. For this purpose, a generalized approach based on the theory of the "representative" vector is used.*

Keywords: *Unbalance, direct and reverse sequence, unbalance coefficients, power supply system, industrial company*

В съвременните технологични процеси внедрявани в индустриалните фирми се забелязва нарастваща тенденция към все по-голямо използване на несиметрични в електрическо отношение потребители.Това се обуславя от факта, че такова обзавеждане притежава редица предимства пред аналогични, но в трифазно изпълнение. Основно те са от технико-икономически характер. Наличието на такъв вид потребители, особено съизмерими по мощност със захранващите електроенергийни източници (индукционни топилни пещи, нагревателни устройства и др.) внасят силови електрически смущения в електроснабдителната система при тяхната експлоатация. В следствие на не симетрия в натоварването от страна на потребителите се получават съставки с права, обратна и нулева

последователност на тока т.е. налице е токова не симетрия. Това водят до влошаване качеството на електрическата енергия с която се захранват останалите потребителите. Предизвиква се допълнително формиране на неактивни компоненти на мощности като, пулсираща и скрита в състава на пълната мощност на електроснабдителните системи. Предизвиква се намаляване на преносната възможност на захранващите системи по активна мощност , увеличават се електрическите загуби, влошава се работата на останалото силово електрообзавеждане, както и други негативни последици за индустриалните фирми Л(1), Л(2), Л(3), Л(5).

Съгласно изискването на БДС коефициентите на не симетрия по напрежение и съответно по ток са регламентирани със следните стойности - KU=2% , KI=5%, определени съгласно зависимостите:

$$K_U=U_2/U_1.100\%, K_I=I_2/I_1.100\% \quad (1)$$

където:

U_2, I_2 – представляват ефективните стойности на напрежението и тока на обратната им последователност

U_1 , I_1 - представляват ефективните стойности на напрежението и тока на правата им последователност

Симетричните съставящи на напрежението и тока се определят аналитично от трифазната система според изразите:

$$U_1=1/3(U_a+a.U_b+a^2.U_c),\ I_1=1/3(I_a+a.I_b+a^2.I_c) \quad (2)$$

$$U_2=1/3(U_a+a^2.U_b+a.U_c),\ I_2=1/3(I_a+a^2.I_b+a^2I_c)$$

където:

U_a, U_b, U_c, и I_a, I_b, I_c представляват съответните комплексни стойности на фазни напрежения и токове от трифазната несиметрично натоварена електроснабдителна система

a, a^2 –оператори:

От изложеното до тук става ясно, че определянето на тези коефициенти характеризиращи състоянието на несиметричното натоварване на електроснабдителната система

на индустриалната фирма минава през значителни математически обработки включително на векторни числа характеризиращи се с модул и фаза на позициониране в равнината. Това прави използването на този класически подход не особено подходящ за експресна практично приложна оценка на не си. В настоящата публикация се представя възможност за определяне коефициентите на не симетрия по напрежение и ток по един удобен и рационален за енергийната практика начин. Същевременно образното изображение от изследването във вид на осцилографиран ходограф носи експресна и нагледно обозрима информация за състоянието на симетрията в електроснабдителната система на индустриалната фирма.

В основата на разработката е приложен обобщен подход базиран на теорията на „изобразяващия“ вектор Λ(4). Това дава възможност електрическите величини напрежения и ток в трифазната електроснабдителна система вместо да се изследват с три уравнения по едно за всяка фаза се осъществява само с едно , но във векторен вид както за напрежението , така и за тока съгласно зависимостите (3)

$$U(t)=2/3(u_a+a.u_b+a^2.u_c) \quad (3)$$

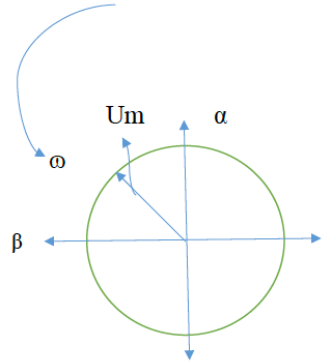
$$I(t)=2/3(i_a+a.i_b+a^2.i_c)$$

където: u_a, u_b, u_c, i_a, i_b, i_c представляват моментните стойности на фазните напрежения и токове

Векторните уравнения (3) за напреженията и токовете от трифазната електроснабдителна система могат да се представят посредством модул и фаза на завъртане на вектора:

$$U(t)=\|U\|.e^{j\omega t} \quad (4)$$

$$I(t)=\|I\|.e^{j\omega t-\varphi}$$



Фиг. 1

На фиг.1 е показан ходографа само на „изобразяващ“ вектор на напрежението при наличие на пълна симетрия в електроснабдителната система. Кривата описана от върха на „изобразяващия“ вектор представлява окръжност с радиус равен на максималната (амплитудна) стойност на напрежението. Графичното представяне на „изобразяващия“ вектор при пълна токова симетрия в електроснабдителната система е аналогичен на този от фиг.1., но в различен мащаб.

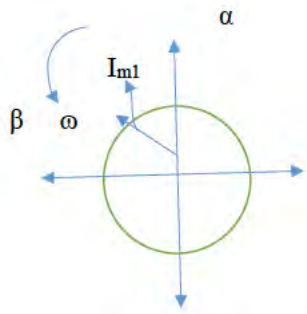
Ходографите на „изобразяващите“ вектори на напрежението и тока са представени в ортогонална (правоъгълна) „αβ“ система, което предварително изисква трансформиране на трифазната координатна система „a b c“ в „α β “.Това се осъществява съгласно известните зависимости (5) например за напрежението:

$$u_\alpha = u_a$$

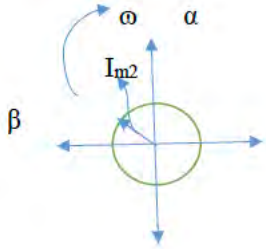
$$u_\beta = (u_b - u_c)/\sqrt{3} \qquad (5)$$

При наличие на неравенство в натоварването по фази на електроснабдителната система възниква едновременно не симетрия в електрическите величини напрежение и ток. Това означава, че възникват съставки в тези ел. величини с права и обратна последователности съгласно посочените зависимости (2). На тази основа могат да се дефинират и „изобразяващи“ вектори за двете последователности. Резултативният „изобразяващ“ вектор за дадената несиметрична електрическа величина се получава от сумирането във времето на двата „изобразяващи“ вектори за права и обратна последователност.

На фиг.2 и фиг.3 са посочени „изобразяващите“ вектори за правата и обратната последователности на несиметричен трифазен ток.

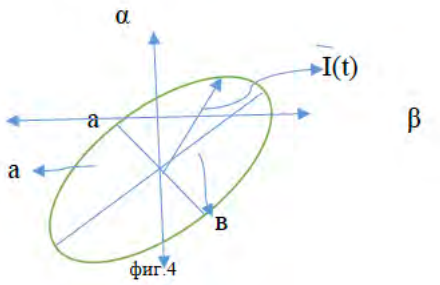


Фиг. 2



Фиг. 3

След сумиране на правата и обратната последователности на токовете с отчитане посоките на въртене на радиус векторите на ходографите се получава резултативния ходограф на несиметричната трифазна токова система, отразена на фиг.4.



Фиг. 4

От фиг. 4 се вижда, че при наличие на не симетрия (в случая токова) ходографа на „изобразяващия“ вектор представлява елипса с малка „в“ и голяма „а“ полуоси. Тези полуоси съответно се определят от равенствата:

$a=I_{m1}+I_{m2}$ (6)

$в=I_{m1}-I_{m2}$

където: I_{m1} и I_{m2} представляват максималните амплитудни стойности на правата и обратна последователности на не симетричната токова система.

Токовете за правата и обратната последователност се определят с изразите:

$$I_{m1}=(a+в)/2 \quad (7)$$

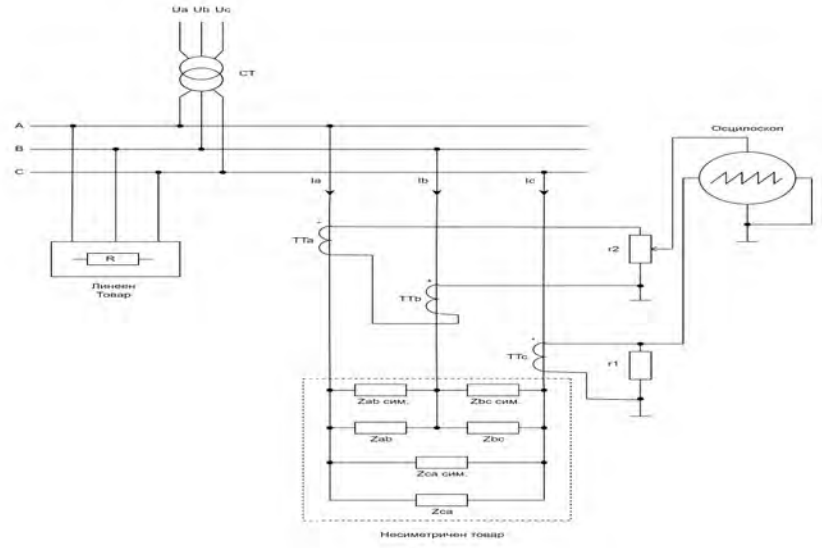
$$I_{m2}=(a-в)/2$$

Поделяйки тези стойности на корен от две получаваме тяхната ефективна стойност, съответно: I1 и I2.

От стойностите на обратната и права последователности при не симетрия по напрежение и ток съгласно (1) се определят съответните коефициенти характеризиращи дадената не симетрия в електроснабдителната система:

$$K_U=U_2/U_1.100\%, K_I=I_2/I_1.100\%$$

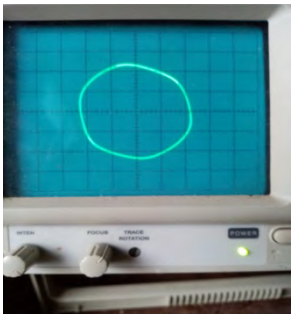
В настоящата публикация са поместени резултати от лабораторни изследвания на постановка на която могат да се реализира както симетрично, така и несиметрично натоварване на имитираната електроснабдителна система фиг.5



Фиг. 5

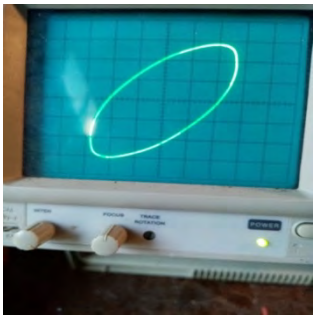
Ходографи на „изобразяващи“ вектори са заснети посредством осцилоскоп, като на двата му входа се подават сигнали пропорционални на потребяваните токове от ел. товар. Тези сигнали от система „a, в, с“ са преобразувани в сигнали за система „α, β“.

На фиг.6 е отразен ходограф на „изобразяващ“ вектор на тока при симетрично токово натоварване. Полученото изображение на екрана на осцилоскопа е почти чиста окръжност.



Фиг. 6

При наличие на не симетрия в токовото натоварване ходографа на „изобразяващия“ вектор на тока е показан на фиг. 7.



Фиг. 7

Ходографа на „изобразяващия“ вектор на тока има форма на елипса. От голямата и малката полуоси на изображението по описания по горе начин се определя коефициента на несиметрия по ток. По същият начин се подхожда при заснет ходограф на напрежението. Този подход осигурява голяма степен на експресна визуализация на процеса за оценка на не симетрията.

Разгледания в публикацията подход за определяне степента на не симетрията в електроснабдителните системи в индустриалните фирми подлежи на по нататъшно развитие и усъвършенстване.

Литература:

1. Крайчик Ю. С. „Метод симетричных составляющих как разновидность метода разложение Фурие" Электричество №8 1990г
2. Жежеленко И. В. „Показатели качество электроэенергии на промышленных предприятиях" Москва, Энергия, 1997
3. Кузнецов В. Г., Григориев А.С., Данилюк В. Б. „Снижение несиметрии и несинусоидальности напрежений в электрических сетях" Киев, Наукова думка 1992
4. Динов В. „Несиметрични режими и преходни процеси в електрическите машини" ДИ Техника – 1974 г
5. Neukirchner, P. Görbe, and A. Magyar, "Voltage unbalance reduction in the domestic distribution area using asymmetric inverters", Journal of Cleaner Production, vol. 142, November 2016

ВЪРХУ ЕДНА ВЪЗМОЖНОСТ ЗА УПРАВЛЕНИЕ НА ФИЛТРО-СИМЕТРИРАЩИ УСТРОЙСТВА В ЕЛЕКТРОСНАБДИТЕЛНИТЕ СИСТЕМИ

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ON ONE POSSIBILITY FOR CONTROLLING FILTER-BALANCED DEVICES IN POWER SUPPLIES

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Abstract: *This publication examines a possibility for managing filter-balancing devices in the power supply systems of industrial companies, in the presence of unsymmetries in them. An analysis is made of the current symmetrization according to the "Steimnets" scheme at different ratios of the power of the asymmetric load and filter-symmetrization elements. The "pulsating" power "N" is applied to assess the electrical unsymmetry. It has been established that an account of the angular dephasing between phase voltage and current can be applied as a control criterion for filter balancing devices.*

Keywords: *electricity supply system, industrial companies, filter-balancing device, asymmetry, pulsating power*

В редица производствено-технологични процеси, относителният дял на мощните несиметрични в електрическо отношение производствени агрегати непрекъснато нараства. Това се обяснява с технико-икономическите предимства, които се реализират с подобни решения. С оглед осигуряване на нормативните изисквания за качеството на електрическата енергия, тези агрегати се окомплектоват с управляеми филтро-симетриращи устройства. Посредством тях се филтрира обратната последователност на несиметричния ток в електроснабдителната система, като по този начин тя токово се

симетрира. Тези устройства основно се състоят от два блока: датчик отчитащ токовата не симетрия и силов филтро-симетриращ блок.

Познатите решения които се прилагат при разработка на датчиците за контрол на не симетричната, основно се разделят на три групи [1,2,3,4]: датчици работещи на принципа на измерване на мощността на не симетричния товар и мощността на филтро-симетриращите елементи, датчици основани на сравняване на токове през несиметричния товар и филтро-симетриращите елементи, както и датчици работещи на принципа на измерване фазовата разлика между симетрираните токове. Към посочените принципни решения могат да бъдат причислени следните недостатъци: към първа група – използване на нестандартни измерители на активна и реактивна мощности, представляващи сравнително скъпи прибори; към втората група зависи от точността на симетриране и наличие на изкривявания във формата на сравняваните токове; към трета група-ниска чувствителност на датчика.

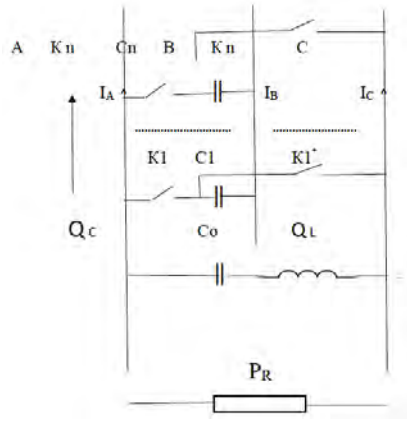
В настоящата публикация се разглежда един подход основан на възможността за използване на появата на „пулсиращата“ мощност „N“ в не симетрично „замърсени“ електроснабдителни системи за управление процеса на токовото филтро-симетриране. Тази неактивна мощност се явява носител на информация за не уравновесеността, респективно уравновесеността (симетрията) в системата. С нейното прилагане като критерий за оценка уравновесеността в системата, се създава възможност за рационализиране на управлението при токовото симетриране в нея. В съвременния контекст на дигитализация, изкуственият интелект все по-често се разглежда като инструмент за подпомагане на психодиагностиката, анализа на данни, скрининга и проследяването на психичното състояние (D’Alfonso, 2020; Graham et al., 2019). Въпреки това интелигентните технологии не следва да заменят психолога, а да подпомагат професионалната му дейност при запазване на етичната отговорност, прозрачността и човешкия контрол (Luxton, 2014; Miner et al., 2019).

Известно е, че при напълно симетрична в електрическо отношение електроснабдителна система, неактивната пулсираща мощност „N" е равна на нула [6]. При това състояние се счита, че системата е напълно уравновесена. Обратно, при наличие на несиметрия в електрическото натоварване се появява „пулсираща"

мощност, като нейната големина е пропорционална на степента на несиметрията. Следователно тази мощност се явява характерна енергетична величина на не симетрично натоварената електроснабдителна система. Това обстоятелство може да се използва като отправен подход за управление на филтро-симетриращите устройства.

В публикацията основно се разглежда възможността за управление на филтро-симетриращи устройства, реализирани по схема „Щаймнец“. Тази схема, състояща се от електрически тип реактивни силови елементи (не от електромагнитни, като специални нестандартни трансформатори и др.), е получила широко приложение в индустриалните фирми.

На фиг. 1 е показана ел. схема на филтро-симетриращо устройство с включен не симетричен ел. товар към него.



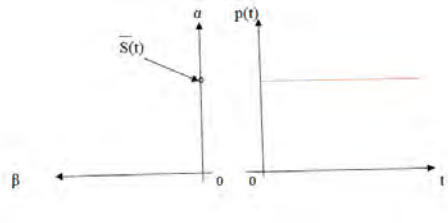
Фиг. 1

Филтро-симетриращия блок се състои от две части, реактивни елемента. Първата част е съставена от набор превключващи кондензаторни групи, които могат да бъдат включени към фази „А“ и „В“ с възможност и за превключване между фази „В“ и „С". Втората група се състои от постоянно включена индуктивност между фази „В“ и „С." Несиметричният ел. товар е присъединен между фази „С“ и „А." Той трябва да бъде „активен“ ел. товар, или да бъде компенсиран до cos φ = 1.00. Мощността на кондензаторните батерии от фиг.1 е обозначена с „QC“, мощността на индуктивността с „QL", а мощността на не симетричния ел. товар с „PR". Условието за осъществяване на пълно токово симетритане на товара се постига тогава, когато

абсолютните стойности на мощностите са в следното съотношение:

$$|Q_C| = |Q_L| = |P_R| /\sqrt{3} \quad (1)$$

Ако енергетичното състояние на електроснабдителната система се оценява с помощта на пълната мощност, като „изобразяващ“ вектор „S" [5], то той има вида показан на фиг.2 а) , т.е. състои се от точка. Развитието на моментната мощност „p(t)", представляваща реалната компонента на пълната мощност "S", е права линия (фиг.2 б).

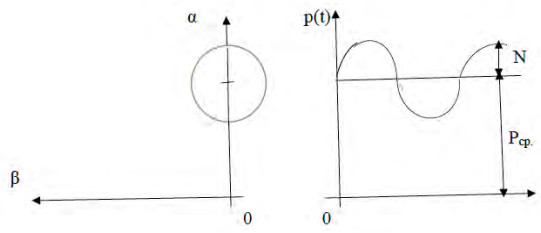


а) *б)*

Фиг. 2

Това развитие на "p(t)" във времето показва, че електроснабдителната система е уравновесена, тоест отсъства смущение от несиметрия.

В случаите когато зависимост (1) не е изпълнена, тогава ходографа на „изобразяващия“ вектор на пълната мощност „S" и изменението на моментната мощност „p(t)" придобиват вида показан на фиг. 3 а) и б).



а) *б)*

Фиг. 3

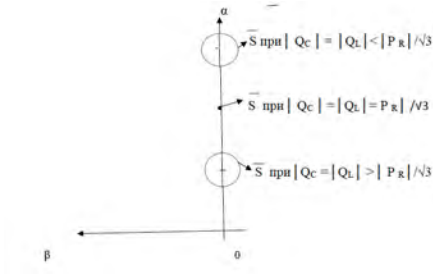
От фиг. 3 се вижда, че поради наличие на смущение от несиметрия в електроснбдителната система, тя е не

уравновесена. Върху постоянната съставяща „P CP“, която представлява консумираната активна мощност от ел. товар, се наслагва променлива съставяща. Амплитудната стойност на тази съставяща определя „пулсиращата" мощност, предизвикана от не симетрията в натоварването [6].

В режим на експлоатация на не симетричния ел.товар са възможни три случая, при съвместната му работа с филтро-симетриращото устройство, които случаи са посочени в зависмости (2).

$$|Q_C| = |Q_L| < |P_R|/\sqrt{3}$$
$$|Q_C| = |Q_L| > |P_R|/\sqrt{3} \qquad (2)$$
$$|Q_C| = |Q_L| = |P_R|/\sqrt{3}$$

На тези възможни случая, като съотношения между реактивните мощности на филтро-симетриращите елементи и потребяваната мощност от несиметричния товар съответстват три различни хадографа на „изобразяващия“ вектор на пълната мощност „S," които са показани на фиг. 4.

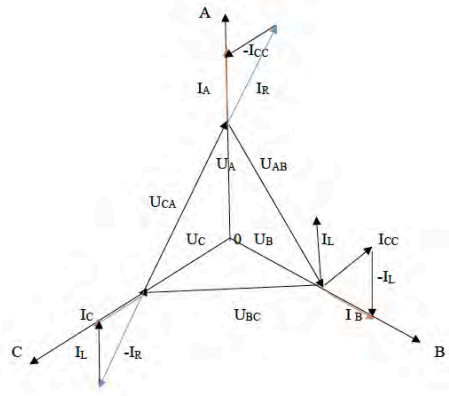


Фиг. 4

От фигурата се вижда, че и в двата случая когато не са изпълнени изискванията на равенство (1), е налице не симетрия в натоварването. В първият случай„ |QC| = |QL| < | R|/√3" за да се получи симетрия в натоварването е необходимо да се увеличи реактивната филтро-симетрираща мощност, а при втория „ |QC| = |QL| > |PR|/√3 случай да се намали. При спазена зависимост (1) е налице пълна токова симетрия, и „изобразяващия" вектор на пълната мощност се редуцира в точка. Следователно при не изпълнение на зависимост (1) възниква „пулсиращата“ мощност „N." Големината на тази мощност носи информация за степента на възникващата не симетрията. Отсъства обаче информация в каква посока трябва да се изменя филтро-

симетриращата мощност (да се увеличава или намалява) за да се постигне токова симетрия. От проведения анализ на този процес за управление на филтро-симетриращата мощност, се стига до следния извод: като изходен параметър за управление на „пулсиращата“ мощност е целесъобразно да се отчита изменението на фазовото изместване между напрежението на фаза „А“ и резултативния вектор съставен от не симетричния ток а товара и тока от кондензаторната батерия за същата фаза.

Векторните диаграми илюстриращи процеса на пълна симетрия и не симетрия в токовото натоварване с отчитане на споменатото фазово изместване между фазовото напрежението и тока са отразени съответно на фиг. 5 а) и б).

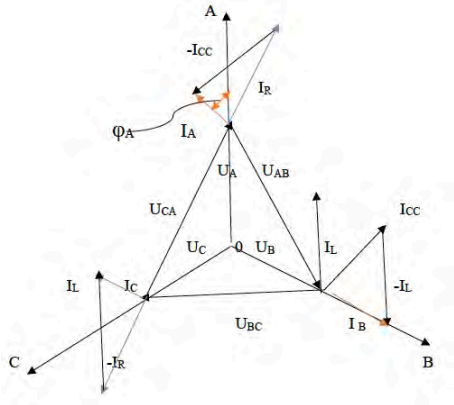


Фиг. 5 а)

От векторната диаграма, посочена на фиг. 5а) се вижда, че при изпълнени условия съгласно израз (1) се получава пълна токова симетрия в натоварването. Трите фазови тока IA, IB и IC са равни по модул и фазово изместени на 120 градуса. Това е необходимо и достатъчно условие на несиметричната система да бъде симетрирана. Ъгловото изместване между фазовите напрежения и съответните токове „φ" е равно на нула. Това взаимно разположение между двата вектора може да се оцени посредством тригонометричната функция „cos φ“. При състояние на симетрия cos φ = 1.00, в този случай отсъства „пулсираща“ мощност „N“, като ходографа на пълната мощност „S“ се редуцира в точка.

При неизпълнение на условието съгласно (1) не се постига токово симетриране. Това се илюстрира с векторната диаграма от фиг. 5 б). Тя е построена за предпоставка, че реактивните мощности на филтро-симетриращите елементи „QC" и „QL" са

равни по между си, но остават по-големи от несиметричната мощност „PR/√3". Схемо – технически равенството между реактивните филтро-симетриращи мощности се осъществява с превключване на кондензаторни групи от фази „А и В“ към фази „В и С." Мощностите на филтро-симетриращите елементи „QC" и „QL" по разглежданата схема за симетриране са определени за максимален несиметричен ел. товар „PR" с възможност за тяхно регулиране. При намаляване мощността на несиметричния товар, се налага да се регулира в посока понижаване мощността на филтро-симетриращите елементи. Това се осъществява с паралелно прехвърляне на кондензаторна мощност към постоянно включената индуктивност между фази „В и С." Ако това не се реализира, възниква „пулсираща“ мощност „N“ от не симетрия. Случаят се илюстрира с векторната диаграма, посочена на фиг. 5 в). Вижда се, че фазовите токове не са симетрични, което е причина за възникване на „пулсираща" мощност.



Фиг. 5 б)

В този разгледан случай, тока от фаза „А“ изостава на ъгъл „φ“ по отношение на фазовото напрежение на същата фаза. Както е установено в по-горния случай на разглеждане (фиг.5а), токовата симетрия се характеризира и с това, че пълно токово симетриране се осъществява при cos φ = 1.00. Може да се заключи, че при управление на филтро-симетриращите елементи се въздейства на „пулсиращата“ мощност и чрез „cos φ." Това дава основание в процес на симетриране да се реализира управление на „cos φ" до стойност равна на единица. За целта в този случай може да се използват стандартно прилагани косинус фи регулатори.

От релейно контактните изходи на регулаторите се включват или изключват кондензаторни групи свързани между фази „А и В“

посредством контакторите „K1 до KN." Изключването и включването на контакторите „K1⁺ до KN⁺", превключващи кондензаторни групи към фази „B и C“ се осъществява в съответствие с включването и изключването на контакторите „K1 до KN" (фиг.1). При ситуация, при която филтро-симетриращата мощност е по малка от мощността на не симетричния товар, тока от фаза „A“ изпреварва на ъгъл „φ“ фазовото напрежение на същата фаза. И в този случай токово симетриране се осъществява отново с постигане на cos φ = 1.00.

В резултат от извършения анализ и оценка на възможността за управление на филтро-симетриращите устройства реализирани по схема „Щаймнец", се прави следното заключение: у*правление процеса на токово симетриране може да се реализира с отчитане на дефазирането между фазовото напрежение и съответният му ток (ъгъл φA, например за конкретната схема от фиг.1). Отговарящия на това фазово изместване косинус фи трябва да се поддържа от регулатор със стойност равна на cos φ = 1.00, посредством превключване на комутируема част от кондензаторни батерии.*

Литература:

1. Гитгардтц Д.А.,Мнухин Л.А. „Симетрирующие устройства для еднофазных электротермических установок“ Энергия, Москва 1974
2. Дрекслер Р. „Измерение и оценка качества электроэенергии при несиметричной и нелинейной нагрузке” Москва „Энергоатомиздат” 1990
3. Neukirchner, P. Görbe, and A. Magyar, “Voltage unbalance reduction in the domestic distribution area using asymmetric inverters," Journal of Cleaner Production, vol. 142, November 2016.
4. Mahir Mahdee, "Investigation of Three-Phase Balancing Techniques," ELEK-TRO-MFE - October 2020
5. Петков П. Д., и кол. „Приложение на изобразяващия вектор за оценка на качеството на електрическата енергия и пълната мощност в електрическите системи.“Научна конференция, посветена на 30-годишнината на ВМЕИ-Габрово, 1994 г.
6. Шидловский А. К., Мостовяк И. В., Москаленко Г. А. „Уравновешивание режимов многофазных цепей” АНУ Институт электродинамики Киев, Наукова думка 1990
7. to Regulation (EU) 2019/2152 of the European Parliament and of the Council (Text with EEA relevance). Official Journal of the European Union [online]. Available at: https://data.europa.eu/eli/reg_impl/2021/1190/oj

INTELLIGENT MODEL FOR SUPPORTING INVESTIGATIVE ANALYSIS IN BURGLARY INVESTIGATIONS

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Abstract: *Modern criminal investigations are characterized by a high degree of uncertainty, incomplete information, and the simultaneous existence of multiple competing investigative hypotheses. During burglary investigations, investigators and criminal analysts are often required to interpret contradictory facts and indirect evidence under conditions of limited time and insufficient data. This creates the need for intelligent analytical models capable of supporting the process of investigative hypothesis generation and evaluation. This study presents an intelligent model based on fuzzy logic intended to support investigative analysis in burglary investigations. The proposed model is implemented as a Mamdani fuzzy inference system developed using MATLAB Fuzzy Logic Toolbox. The system architecture incorporates twelve input variables related to forensic, behavioral, and situational indicators, as well as five output investigative hypotheses representing different possible criminal scenarios. The paper examines the processes involved in selecting input and output parameters, constructing membership functions, developing the rule base, and implementing fuzzy inference and defuzzification mechanisms. Results obtained from the analysis of real judicial cases are also presented in order to evaluate the practical applicability of the proposed system. The obtained results demonstrate that fuzzy logic represents an appropriate approach for modeling investigative analytical processes under conditions of uncertainty and incomplete information. The proposed model demonstrates the potential for intelligent support of investigative authorities during the generation and prioritization of investigative hypotheses.*

Keywords: *fuzzy logic, criminal analysis, investigative hypotheses, expert systems, burglary investigations, intelligent systems, fuzzy inference systems*

I. INTRODUCTION

Criminal investigation represents a complex analytical process involving the collection, interpretation, and evaluation of various types of evidential and operational information. In investigative practice, information

is frequently incomplete, contradictory, or uncertain, which significantly complicates the process of developing objective investigative hypotheses. This problem is particularly evident in burglary investigations, where similar criminal circumstances may support different interpretations depending on the available forensic traces, offender behavior, and characteristics of the target location. Traditional investigative analysis is largely based on professional experience, intuition, and subjective assessment by investigators. Although expert knowledge remains essential, the absence of formalized analytical mechanisms may lead to cognitive bias, inconsistency in evidence evaluation, and premature prioritization of specific investigative hypotheses. The rapid development of artificial intelligence and expert systems has created opportunities for designing intelligent analytical models capable of supporting criminal investigations. One of the approaches particularly suitable for modeling uncertainty in forensic analysis is fuzzy logic, introduced by Lotfi Zadeh in 1965. Unlike classical binary logic, fuzzy logic enables the use of linguistic variables and gradual transitions between analytical states.This characteristic is especially important in investigative practice, where indicators such as “strong forced entry,” “high probability of conspiracy,” or “partial identification” cannot be evaluated using strictly binary categories. Fuzzy logic allows the simultaneous partial activation of multiple investigative hypotheses, which more accurately reflects the real process of investigative reasoning.This paper presents an intelligent model for supporting investigative analysis in burglary investigations based on a Mamdani fuzzy inference architecture. The primary objective of the study is to demonstrate the applicability of fuzzy logic for the development of an expert system intended to support the generation and prioritization of investigative hypotheses under conditions of uncertainty and incomplete information.

II. THEORETICAL FOUNDATIONS OF FUZZY LOGIC

Fuzzy logic represents a mathematical approach for modeling uncertainty and approximate reasoning. Unlike classical logic, where membership in a set is binary and limited to values of either 0 or 1, fuzzy sets allow partial membership expressed through values within the interval [0,1]. One of the fundamental components of fuzzy logic is the membership function, through which numerical values are transformed into linguistic categories such as “low,” “medium,” and “high.” This enables the formalization of expert knowledge and the modeling of human analytical reasoning. In forensic and investigative practice, many indicators possess precisely such uncertain characteristics. For example, the degree of forced entry, the level

of criminal organization, or the probability of offender collaboration cannot be adequately evaluated using strictly binary criteria. For this reason, fuzzy logic is particularly suitable for the development of systems intended to support investigative analysis. The proposed model utilizes a Mamdani fuzzy inference architecture because this approach provides high interpretability and enables the direct construction of IF–THEN rules based on expert knowledge and forensic investigative practice.

III. ARCHITECTURE OF THE PROPOSED MODEL

The proposed model is implemented as an expert system based on fuzzy inference. The architecture consists of several sequential stages: input data acquisition, fuzzification, rule base processing, fuzzy inference, aggregation, and defuzzification. Input data are formed from forensic and situational indicators obtained during the criminal investigation process. These indicators are transformed into linguistic values through membership functions and subsequently processed by the fuzzy rule base. The system utilizes a Mamdani fuzzy inference mechanism with min-max composition and centroid defuzzification. As a result, numerical values are generated representing the degree of analytical support for each investigative hypothesis. The proposed model is designed to support the analytical reasoning process without replacing the expert evaluation performed by investigative authorities. Its primary purpose is to structure the available information and assist in the generation of justified investigative hypotheses under conditions of uncertainty.

IV. INPUT AND OUTPUT PARAMETERS OF THE SYSTEM

One of the most significant stages in the development of the proposed intelligent model is the selection of input and output parameters. The variables were selected on the basis of criminological theory, analysis of real judicial cases, and the logic of investigative reasoning in burglary investigations. The model utilizes twelve input variables describing different aspects of criminal activity, offender behavior, and crime scene characteristics. Each variable is evaluated within the interval from 0 to 10 and subsequently transformed into linguistic values through membership functions. The input parameters include degree of forced entry, use of technical tools, displacement of objects, value and scope of missing property, serial behavior, coordination between participants, disposal of stolen property, strength of forensic identification, previous criminal activity, existence of alternative explanations, insurance-related interest, and knowledge of the target location. The selection of these indicators allows simultaneous

consideration of both objective forensic traces and behavioral or situational characteristics. This is particularly important in the development of intelligent criminal analysis systems, since real investigations rarely rely exclusively on direct evidence.The output of the system consists of five investigative hypotheses representing different possible interpretations of the criminal event. The model generates degrees of analytical support for the following versions: serial or professional burglary, opportunistic or isolated burglary, coordinated participation or conspiracy, alternative explanation, and staged event motivated by insurance fraud. Instead of generating a single final decision, the system allows simultaneous partial activation of multiple hypotheses. In this way, the model reflects the actual process of investigative reasoning, where several competing hypotheses may coexist during the analytical phase of criminal investigation.

V. IMPLEMENTATION OF THE FUZZY INFERENCE SYSTEM

The proposed intelligent model was implemented in MATLAB using the Fuzzy Logic Toolbox environment. A Mamdani fuzzy inference architecture was selected due to its high interpretability and its ability to represent expert knowledge through rules closely resembling natural investigative reasoning. Each input variable is represented through three linguistic values: “low,” “medium,” and “high.” Triangular and trapezoidal membership functions were used to model these categories. The use of three linguistic levels allows a balance between analytical flexibility and system interpretability. The membership functions were designed to provide smooth transitions between neighboring categories. This enables partial membership of a given value in multiple fuzzy sets simultaneously, which is one of the principal characteristics of fuzzy logic systems. The rule base represents the core analytical mechanism of the proposed system. The rules were developed through the analysis of real judicial cases and forensic investigative expertise. Each rule describes a relationship between a combination of input indicators and a corresponding investigative hypothesis. For example, the simultaneous presence of a high degree of forced entry, use of technical tools, serial criminal behavior, and previous criminal activity increases the activation of the hypothesis related to professional or serial burglary. In cases involving strong insurance-related interest and alternative explanations, the system increases the degree of support for the staged-event hypothesis. The fuzzy inference mechanism utilizes the min operator for logical conjunction and the max operator for aggregation of activated rule outputs. Final results are generated through centroid

defuzzification, allowing the system to produce numerical evaluations for each investigative hypothesis. The architecture of the proposed model enables future expansion through the addition of new variables, rules, and optimization mechanisms. This creates opportunities for adapting the system to different categories of criminal investigations and more complex forensic scenarios.

VI. ANALYSIS OF REAL JUDICIAL CASES

In order to evaluate the practical applicability of the proposed model, an analysis was performed using fifteen real judicial cases related to burglary investigations. The selected cases included different criminal scenarios such as serial offenses, isolated criminal acts, coordinated participation, alternative explanations, and suspected staged events. For each case, the input parameters were evaluated using numerical values within the interval from 0 to 10 and subsequently processed by the fuzzy inference system. The obtained results represent the degree of analytical support for each investigative hypothesis. The analysis demonstrated that the model successfully differentiates between various criminal scenarios and generates results corresponding to the factual circumstances of the investigated cases. In cases involving serial criminal behavior, the system generated high levels of support for the "serial/professional burglary" hypothesis, whereas cases involving limited losses and lack of organization resulted in stronger activation of the opportunistic burglary hypothesis. An especially important characteristic of the model is its ability to simultaneously partially activate multiple investigative hypotheses. This enables more realistic modeling of the analytical reasoning process and reduces the risk of prematurely excluding alternative investigative versions. The obtained results confirm the applicability of fuzzy logic for the development of intelligent systems intended for criminal analysis and investigative decision support. The proposed system does not replace the expert evaluation of investigative authorities but functions as an analytical instrument for structuring and prioritizing investigative hypotheses.

VII. ADVANTAGES, LIMITATIONS, AND FUTURE DEVELOPMENT

The proposed intelligent model offers several important advantages for supporting investigative analysis under conditions of uncertainty and incomplete information. First, the system provides transparency and interpretability of the analytical reasoning process. Unlike many contemporary black-box models in artificial intelligence, fuzzy inference systems enable

clear traceability of the relationship between input indicators and generated investigative hypotheses. Another significant advantage of the proposed model is its ability to simultaneously evaluate multiple competing hypotheses. In real investigative practice, available evidence rarely supports only a single version of the criminal event. Fuzzy logic enables the modeling of such analytical uncertainty and supports more objective structuring of the investigative process. An additional advantage is the modular architecture of the system. The model can be extended through the inclusion of new forensic indicators, additional rules, and adaptive optimization mechanisms. This creates opportunities for future application in other categories of criminal investigations. Alongside these advantages, several limitations should also be acknowledged. The effectiveness of the system depends significantly on the quality of the rule base and the expert knowledge used during model construction. Certain atypical criminal scenarios may not be sufficiently represented within the existing rule structure. Future development of the system is associated with expanding the database of real judicial cases, optimizing membership functions, and developing a graphical user interface intended for practical use in investigative analytical activities. Another promising research involves the integration of adaptive neuro-fuzzy mechanisms and machine learning methods for automated optimization of the rule base.

VIII. CONCLUSION

This study presented an intelligent model for supporting investigative analysis in burglary investigations implemented through fuzzy logic and a Mamdani fuzzy inference architecture. The proposed model demonstrates the possibility of formalizing forensic expert knowledge and modeling analytical processes under conditions of uncertainty and incomplete information. The developed system utilizes twelve input variables and five investigative hypotheses through which intelligent support for the generation and evaluation of investigative versions is achieved. Through the use of membership functions, fuzzy rules, and defuzzification mechanisms, the model enables simultaneous partial activation of multiple competing hypotheses, which more accurately reflects the real logic of criminal analysis. The results obtained from the analysis of real judicial cases demonstrate that fuzzy logic represents an appropriate approach for the development of expert systems in the fields of criminalistics and investigative analysis. The model is not intended to replace expert evaluation by investigative authorities but rather to provide an analytical framework for structuring and prioritizing investigative hypotheses. The proposed approach establishes a

foundation for future development of intelligent criminal analysis systems, including adaptive models, graphical interfaces, and integration with larger forensic data environments.

References:

1. L. A. Zadeh, “Fuzzy Sets,” Information and Control, vol. 8, no. 3, pp. 338–353, 1965.
2. T. J. Ross, Fuzzy Logic with Engineering Applications, 3rd ed. Wiley, 2010.
3. G. J. Klir and B. Yuan, Fuzzy Sets and Fuzzy Logic: Theory and Applications. Prentice Hall, 1995.
4. J.-S. R. Jang, C.-T. Sun, and E. Mizutani, Neuro-Fuzzy and Soft Computing. Prentice Hall, 1997.
5. E. H. Mamdani, “Application of Fuzzy Algorithms for Control of Simple Dynamic Plant,” Proceedings of the Institution of Electrical Engineers, vol. 121, no. 12, pp. 1585–1588, 1974.
6. S. Russell and P. Norvig, Artificial Intelligence: A Modern Approach, 4th ed. Pearson, 2020.
7. D. Dubois and H. Prade, Fuzzy Sets and Systems: Theory and Applications. Academic Press, 1980.
8. C. Kahraman, Fuzzy Applications in Industrial Engineering. Springer, 2006.
9. A. P. Engelbrecht, Computational Intelligence: An Introduction, 2nd ed. Wiley, 2007.
10. MathWorks, Fuzzy Logic Toolbox User’s Guide. MathWorks Inc., Natick, Massachusetts, USA, 2024.
11. I. Nenov, Criminalistics. Sofia: Siela Publishing, 2018.
12. N. Radulov, Information Systems and Security. Sofia: New Bulgarian University Press, 2019.
13. V. Vuchkov, Criminal Analysis and Investigation. Sofia: Feneya Publishing, 2016
14. M. Marinov, Theory of Criminalistics. Sofia: Labor and Law Publishing, 2015.
15. I. Ivanov, “Application of Artificial Intelligence in Security Systems,” Scientific Proceedings of Nikola Vaptsarov Naval Academy, 2021.

POLICIES, REGULATIONS AND SUSTAINABLE BUSINESS MODELS FOR ADVANCING THE CIRCULAR ECONOMY: EVIDENCE FROM BULGARIA

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Abstract: *This paper examines the role of policies, regulations, and sustainable business models in promoting the circular economy in Bulgaria. It analyzes the opportunities for more efficient resource use, waste reduction, and the stimulation of sustainable economic practices in line with the European goals for sustainable development. Special emphasis is placed on the importance of the "polluter pays" principle, the need to improve the regulatory framework, and the strengthening of control mechanisms. The study also explores the challenges associated with implementing circular models in key sectors of the Bulgarian economy, as well as the innovative opportunities for their development through digital technologies, modern regulatory instruments, and effective resource management.*

Keywords: *circular economy, sustainable business models, green policies, resource efficiency, digital transformation, Bulgaria*

1. Introduction

The transition to a circular economy requires Bulgaria to modernize its political, regulatory, and economic framework so that it aligns with the European objectives for sustainable development and resource efficiency. Despite the EU's clear strategic direction, the national implementation of circular models remains fragmented and is largely determined by the effectiveness of regulations, control mechanisms, and the readiness of businesses to integrate sustainable practices. In this context, the „polluter pays" principle, digital transformation, and the development of sustainable business models acquire key importance, as they can improve resource management and reduce waste. Bulgaria has the potential to accelerate the circular transition through the adoption of innovative solutions, modern regulatory instruments, and more effective cooperation between institutions, businesses, and technology.

This report examines the political and regulatory framework, the challenges to applying circular models, and the innovative opportunities for development in Bulgaria, with a particular focus on the role of digital technologies and sustainable business models in achieving long-term resource efficiency.

2. European Policies and Regulations

The European Union plays a key role in the transition to a circular economy by establishing a comprehensive strategic and regulatory framework aimed at sustainable resource use and waste reduction. A central strategic document in this direction is the *European Green Deal*, which sets the objective of achieving climate neutrality by 2050 and transforming the EU economy into a sustainable model [1]. Within this strategy, the *Circular Economy Action Plan* (2020) outlines a set of measures covering the entire life cycle of products—from their design to waste management. Particular emphasis is placed on ecodesign, waste reduction, extending product lifespans, and the use of secondary raw materials. The plan targets key sectors such as electronics, textiles, plastics, construction, and the food industry [2]. Despite progress in policy implementation, the share of secondary materials used in the EU economy remains relatively low—around 11–12%, according to Eurostat data. In response to these challenges, the EU aims to significantly increase this share by 2030, enhancing resource efficiency and reducing dependence on primary raw materials [3]. Furthermore, the regulatory framework is expanding through the introduction of new mechanisms for transparency and product traceability, including the concept of the *Digital Product Passport*, which forms part of the new ecodesign regulation and aims to facilitate recycling and reuse [4].

Overall, European policies not only establish the normative foundation for the circular economy but also act as a catalyst for accelerating the transition through stricter regulations, enhanced traceability, and incentives for sustainable production practices.

3. Bulgarian Regulatory Framework and Challenges

Bulgaria implements the European Union's circular economy policies through a national legislative and institutional framework, primarily defined by the Waste Management Act [5] and the Environmental Protection Act [6]. These legal instruments transpose EU directives and establish the requirements for waste prevention, separate collection, recycling, and recovery. The institutional framework includes the Ministry

of Environment and Water (MOEW) and the Executive Environment Agency (EEA), which are responsible for policy implementation, monitoring, and enforcement of environmental legislation [7]. Despite the existence of a regulatory framework, the implementation of circular models in Bulgaria remains limited due to several structural challenges. These include the insufficient effectiveness of control mechanisms, weak coordination between institutions, and the limited incentives for businesses to invest in sustainable practices. As a result, the application of European requirements is uneven, leading to delays in the transition toward a more sustainable economy.

An additional challenge is the limited development of systems for efficient separate collection and recycling, as well as the insufficient integration of circular economy principles into industrial and energy policies. As a result, a significant share of resources is not reintroduced into the economic cycle, which reduces resource efficiency at the national level. According to Eurostat data, Bulgaria remains among the countries with a relatively low share of circular material use in the economy, which underscores the need for more effective regulatory instruments and strengthened enforcement of environmental policies [8]. Overall, the national regulatory framework is formally aligned with European requirements, but its practical implementation requires further strengthening of institutional capacity, control mechanisms, and economic incentives for businesses.

4. Polluter „Pays Principle“

The „polluter pays“ principle is a fundamental mechanism in the environmental policy of the European Union, aimed at introducing economic responsibility for environmental damage. It requires that the costs of preventing, controlling, and remedying pollution be borne by the entities that cause it, thereby creating incentives for waste reduction and more efficient resource management. In the European regulatory framework, the principle is integrated into a number of directives, including those on waste management, environmental liability [9], and extended producer responsibility. These instruments serve as the basis for introducing fees, penalties, and economic mechanisms designed to limit pollution and encourage sustainable production practices. In Bulgaria, the principle is formally introduced through the Environmental Protection Act and the related secondary legislation. However, its practical implementation remains challenging due to the insufficient effectiveness of control mechanisms, limited administrative capacity, and the mismatch

between the level of sanctions and the actual environmental damage. In many cases, economic penalties do not lead to changes in the behaviour of polluters, which reduces the deterrent effect of the regulation. In the context of the circular economy, the „polluter pays“ principle acquires new significance, as it can be reinforced through digital tools for traceability and accountability. Technologies such as the Internet of Things (IoT), blockchain, and digital product passport systems enable the tracking of resources and waste throughout the entire life cycle of products. This creates conditions for more accurate identification of responsibility, more effective enforcement of sanctions, and stronger incentives for companies to reduce their environmental footprint. Effective implementation of the principle is essential for accelerating the circular transition in Bulgaria, as it creates economic incentives for reducing waste, improving resource efficiency, and adopting innovative solutions. In this sense, it represents an important foundation for developing the innovative opportunities for progress discussed in the next section of the report.

5. Recommendations for Improving Resource Efficiency and Accelerating the Circular Economy in Bulgaria

Accelerating the circular transition in Bulgaria requires an integrated approach that combines technological innovation, modern regulatory instruments, and effective resource management. On this basis, several key development directions can be formulated.

First, more efficient use of generated renewable energy, particularly from photovoltaic systems, is essential. This includes the deployment of intelligent grid-management systems based on artificial intelligence and machine learning, which enable forecasting of production and consumption, reduction generation and create new economic opportunities of losses, and optimization of energy flows. The development of energy-storage systems and smart grids is crucial for enhancing the flexibility and resilience of the energy system.

Second, the implementation of the „polluter pays“ principle can be significantly improved through digital traceability of resources and products. Technologies such as the Internet of Things (IoT), blockchain, and digital product passport systems allow for tracking material flows throughout the entire life cycle of products. This creates conditions for more accurate identification of pollution responsibility, more effective application of environmental charges, and stronger incentives for enterprises to reduce their environmental footprint.

Third, it is necessary to develop sustainable business models that support the circular economy. These include Product-as-a-Service models, repair and refurbishment, reuse, and the extension of product lifecycles. Such models reduce waste for enterprises, particularly in sectors with a high resource footprint.

Fourth, Bulgaria can accelerate the circular transition by promoting industrial symbiosis, in which the waste or by-products of one enterprise become a resource for another. This requires the creation of digital platforms for resource exchange, as well as incentives for companies to participate in such networks.

Fifth, the lifecycle management of photovoltaic panels and other technological products must be improved through the establishment of systems for collection, recycling, and reuse of components. This is particularly important given the growing number of installations and the expected increase in waste from end-of-life panels.

Overall, the integration of renewable energy sources, digital technologies, sustainable business models, and traceability mechanisms represents a key tool for enhancing resource efficiency and ensuring the practical application of circular economy principles in Bulgaria. These approaches provide a foundation for accelerating the transition toward a sustainable economic model and for developing innovative solutions that can strengthen the competitiveness of the national economy.

6. Conclusion

The transition to a circular economy in Bulgaria requires the consistent implementation of European policies, the modernization of the national regulatory framework, and active support for sustainable business models. The analysis shows that, despite formal alignment with European requirements, practical implementation remains hindered by limited institutional capacity, insufficient coordination, and weak control mechanisms. This slows the adoption of circular solutions and reduces the effectiveness of the „polluter pays“ principle. At the same time, Bulgaria has real potential to accelerate the circular transition through the integration of digital technologies, traceability systems, and innovative management tools. Technologies such as artificial intelligence, IoT, blockchain, and digital product passports can enhance transparency, optimize resource flows, and support more effective enforcement of regulatory requirements. Sustainable business models, industrial symbiosis, and the development of intelligent energy systems further expand the opportunities for improving resource efficiency. In conclusion,

sustainable development and the circular economy in Bulgaria can be achieved through an integrated approach that combines policies, regulations, technological innovation, and economic incentives. Only through their alignment is it possible to achieve a genuine transformation toward a sustainable economic model that enhances the competitiveness of the national economy and supports long-term goals for resource efficiency and environmental sustainability.

References:

1. BRODNY, J. i TUTAK, M., 2022. Digitalization of small and medium-sized enterprises and economic growth: Evidence for the EU-27 countries. Journal of Open Innovation: Technology, Market, and Complexity, 8(2), art. 67. https://doi.org/10.3390/joitmc8020067
2. European Commission (2019). *The European Green Deal*. Brussels: European Commission. The European Green Deal - European Commission [Viewed 2025-6-01].
3. European Commission (2020). *Circular Economy Action Plan: For a Cleaner and More Competitive Europe*. Brussels: European Commission. Circular Economy - Environment - European Commission [Viewed 2025-6-01].
4. Eurostat (2023). *Circular material use rate*. Luxembourg: Eurostat. [cei_srm030] Circular material use rate [Viewed 2025-6-01].
5. European Commission (2023). *Digital Product Passport Framework*. Brussels: European Commission.
6. Министерство на околната среда и водите (2023). *Закон за управление на отпадъците*. София: МОСВ. Available at: Lex.bg - Закони, правилници, конституция, кодекси, държавен вестник, правилници по прилагане [Viewed 2025-6-01]
7. Министерство на околната среда и водите (2023). *Закон за опазване на околната среда*. София: МОСВ. Available at: Lex.bg - Закони, правилници, конституция, кодекси, държавен вестник, правилници по прилагане [Viewed 2025-6-01]
8. Министерство на околната среда и водите (2024). *Официален сайт на МОСВ*. София: МОСВ. Available at: Министерство на околната среда и водите | МОСВ [Viewed 2025-6-01]
9. Eurostat (2023). *Circular economy statistics*. Luxembourg: Eurostat.
10. European Parliament and Council (2004). *Directive 2004/35/EC on environmental liability*. Brussels: EU. Directive - 2004/35 - EN - EUR-Lex [Viewed 2025-6-01].

CHALLENGES RELATED TO PERMIT REGIMES AND INSURANCE IN THE EXCLUSIVE MARITIME ZONES OF THE BLACK SEA: A SECURITY-ORIENTED ANALYSIS

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Abstract: *The Black Sea region is gaining increasing strategic importance in the context of international security, energy supply and global logistics chains. This paper analyses the challenges related to permit regimes and insurance mechanisms in the exclusive economic zones (EEZs) of the Black Sea, focusing on the security of shipping, energy infrastructure and international trade. The study examines the impact of geopolitical conflicts, military risks, hybrid threats and legal fragmentation on maritime activities in the region. The analysis shows that rising insurance premiums, more complex permit regimes and growing insecurity in maritime spaces have a serious impact on the resilience of the maritime economy and regional stability.*

Keywords: *Black Sea, exclusive economic zone, maritime security, insurance, war risk, permit regimes, shipping, hybrid threats*

Introduction

The Black Sea is a strategic transport, energy and geopolitical corridor linking Europe, the Caucasus, the Middle East and Central Asia. After the start of the military conflict between Russia and Ukraine, the region turned into a high-risk area for international shipping, energy infrastructure and trade routes. In this dynamic and tense environment, permit regimes and insurance mechanisms in the exclusive economic zones (EEZs) acquire critical importance. Beyond their traditional administrative and legal functions, they increasingly perform a role in risk management and the protection of national, international and food security in the Black Sea region. The growing number of incidents in the Black Sea, such as attacks on commercial vessels, the danger of sea mines, GPS interference and the use of unmanned maritime systems, is changing the traditional way of assessing maritime risk. This leads to a significant increase in war-risk insurance

premiums and to more complicated procedures for access to and use of maritime zones.

Discussion

The Law on the Maritime Spaces, Inland Waterways and Ports of the Republic of Bulgaria, in line with generally recognised principles and rules of international law and international treaties to which Bulgaria is a party, defines the country's maritime spaces. According to Article 5, paragraph 1, "The maritime spaces of the Republic of Bulgaria comprise the internal maritime waters, the territorial sea, the contiguous zone, the continental shelf and the exclusive economic zone." [1] An illustration from 2024 by the Black Sea Basin Directorate, prepared in connection with the Environmental Assessment of the Marine Strategy for the Protection of the Environment in the Marine Waters of the Republic of Bulgaria and the Programme of Measures for the period 2022–2027, visualises the legally established maritime territories of Bulgaria.

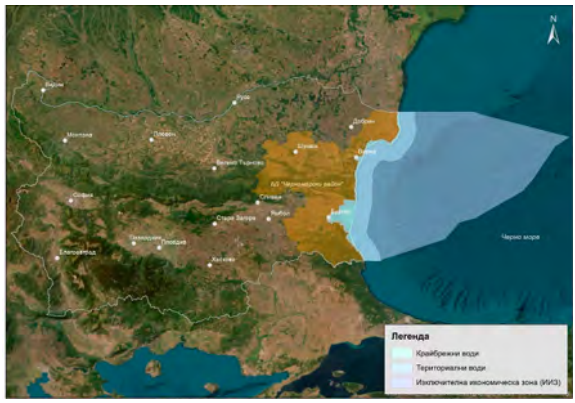


Fig 1. Territorial scope of the Marine Strategy of the Republic of Bulgaria

The specific features of the exclusive economic zone are highlighted in Article 5, paragraph 3, which states that "In the contiguous zone, the continental shelf, and the exclusive economic zone, the Republic of Bulgaria exercises sovereign rights, jurisdiction, and control as defined by this law." [2] The United Nations Convention on the Law of the Sea (UNCLOS), in Article 55, defines the exclusive economic zone as "an area beyond and adjacent to the territorial sea, subject to the specific legal regime established in this Part, under which the rights and jurisdiction of the coastal State and the rights and freedoms of other States are governed by the relevant provisions of this Convention." [3]

The EEZ extends up to 200 nautical miles from the baselines from which the breadth of the territorial sea is measured. Under Article 56 of UNCLOS, within this maritime area the coastal state has:

- sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources of the waters superjacent to the seabed and of the seabed and its subsoil, as well as with regard to other activities for the economic exploitation and exploration of the zone;
- jurisdiction, as provided for in the relevant provisions of the Convention, with regard to the establishment and use of artificial islands, installations and structures, marine scientific research, and the protection and preservation of the marine environment;
- other rights and duties provided for in the Convention. [4]

The scope of Bulgaria's rights and jurisdiction in the EEZ of the Black Sea is further specified in Article 47 of the Law on the Maritime Spaces, Inland Waterways and Ports of the Republic of Bulgaria;

"It states that in the exclusive economic zone the Republic of Bulgaria exercises:

1. sovereign rights for exploration, development, use, conservation and management of biological, mineral and energy resources found on the seabed, in its subsoil and in the overlying waters, as well as for other activities related to the exploration and use of the zone;

2. exclusive rights and jurisdiction related to:

a) the establishment and use of artificial islands, installations and facilities;

b) the conduct of marine scientific research;

c) the protection of the marine environment;

3. other rights deriving from international treaties to which the Republic of Bulgaria is a party and from generally recognised principles and rules of international law". [5] This gives Bulgaria the right to exploit living and non-living natural resources in its EEZ, including the extraction of oil and natural gas; the construction of energy infrastructure, such as facilities generating energy from waves; the conduct of scientific research; and the application of measures for the protection of the marine environment. Under international and Bulgarian law, all states enjoy freedom of navigation, overflight and the laying of cables and pipelines in the EEZ, but foreign vessels may not engage in industrial fishing unless a specific agreement on this activity exists.

The Black Sea is an enclosed inland sea with a limited water area and short distances between coastal states. Schematic maps from sources such

as Marineregions.org show the current distribution of the EEZs in the Black Sea. [6]



Fig 2. Distribution of exclusive economic zones in the Black Sea

The specific character of the sea gives rise to complex questions about the delimitation of maritime spaces, jurisdiction and permit regimes. In general, permit regimes stem from Article 47 of the Bulgarian law and include:

- licences for energy activities;
- licences for exploration and extraction;
- permits for scientific research;
- fishing quotas;
- permits for laying underwater installations;
- permits for the discharge of waste;
- permits related to the control of navigation and port activities.

In the Black Sea there is no single coordinated mechanism among the coastal states, which leads to administrative fragmentation and increased legal uncertainty. Permit regimes are directly affected by geopolitical instability, politicisation and hybrid threats. Since 2022 the Black Sea has become a key area of military and strategic confrontation. The region faces a number of challenges, such as:

- military operations in the vicinity of commercial routes;
- the danger of mines;
- the blocking of sea corridors;
- restrictions on freedom of navigation;
- increased military presence.

According to an analysis by the Royal United Services Institute, the Black Sea is of critical importance for European security and for the

control of energy and food-supply routes, and there has been a notable increase in asymmetric maritime threats, including the use of unmanned maritime systems and sea mines. [7] Permit regimes are increasingly used as an instrument of political influence and to restrict access to certain maritime spaces. This creates difficulties for international energy companies, risks for investment projects, delays in infrastructure initiatives and tension between coastal states. Particularly sensitive remain the areas around Crimea and the north-western part of the Black Sea. Modern maritime threats go beyond traditional military risks, and in the region we see, among others:

- GPS spoofing and electronic interference;
- cyberattacks against port infrastructure;
- sabotage of underwater communications;
- the use of the so-called “shadow fleet.”

Regarding the first three in 2026, the French newspaper Le Monde reported widespread cases of navigational disruptions in the Black Sea and other strategic sea corridors. [8] This creates enormous risks of collusions due to loss of control of commercial vessels.

As for the “shadow fleet," these are mainly tankers used to circumvent sanctions or restrictions on the trade in oil and petroleum products. The phenomenon emerged around 2018–2019, when the United States tightened sanctions on Iran and Venezuela, and after the start of the Russian invasion of Ukraine, the number of vessels in the shadow fleet operating in or around the Black Sea increased sharply.

War risk has become a key factor in determining insurance premiums in the Black Sea. International insurers currently classify parts of the region as "high-risk areas." In 2025 and 2026 international media reported sharp increases in war-risk insurance after attacks on tankers in the Black Sea, with some premiums reaching around 1% of a vessel’s value for a seven-day cover period. This in turn leads to:

- higher overall transport costs;
- restrictions on shipping;
- diversion to alternative routes;
- reduced investment activity.

The unstable security environment has led to additional war-risk clauses, and an increasing number of insurers require:

- special war-risk add-ons;
- short-term policies;
- daily reassessment of risk;

- limited cover for certain ports.

According to Reuters and Insurance Business, in 2025, some insurance companies will start updating their policy terms daily, instead of every 48 hours, due to the dynamic security environment in the Black Sea.

The shadow fleet represents a serious risk to maritime security and the insurance sector, because many of these vessels sail without adequate insurance cover, use false registrations, switch off their Automatic Identification System (AIS) and avoid international control. European institutions and international experts warn that poorly regulated and poorly maintained ships increase the risk of environmental incidents and maritime accidents. The Black Sea is of key importance for grain exports, the transport of oil and natural gas, Europe's energy security and international logistics chains. Instability in the region affects energy prices, transport costs, food markets and the resilience of global supply chains. Insurance restrictions and limited access to maritime spaces can lead to serious economic consequences for the states in the region. The maritime industry, like all other socio-economic activities, is increasingly dependent on digital technologies. Their introduction brings many advantages but also new risks, including:

- the possibility of compromising navigation systems;
- manipulation of AIS data;
- cyberattacks against port information systems.

Studies on maritime cybersecurity show that seafarers and operators have already experienced GPS spoofing incidents and logistical disruptions caused by cyberattacks. These threats complicate risk assessment by insurers and increase costs for maritime operators. Given the above, some of the recommendations relate to the harmonisation of permit regimes, the development of regional insurance mechanisms and the strengthening of international cooperation. Harmonisation of permit regimes could be achieved through coordinated action among the Black Sea states, the development of common security standards, the simplification and alignment of administrative procedures and the creation of specialised mechanisms to cover war risks. NATO, the EU and the International Maritime Organization (IMO) have an active role to play in guaranteeing freedom of navigation, protecting critical infrastructure, coordinating crisis responses, and countering hybrid threats.

Conclusion

The challenges related to permit regimes and insurance coverage in the exclusive maritime zones of the Black Sea are becoming increasingly important in the context of international security and the resilience of the maritime economy. Armed conflicts, hybrid threats, cyber risks and legal fragmentation create a complex environment for international shipping and energy projects. Higher insurance premiums and restricted access to certain maritime spaces have a direct impact on global logistics and energy chains linked to the Black Sea region. An integrated approach is needed, based on international cooperation, modernisation of insurance mechanisms and strengthening of legal certainty in the region. Only through coordinated action by states, international organisations and the private sector can the resilience and security of maritime activities in the Black Sea be ensured.

References:

1. The Law on Maritime Spaces, Inland Waterways and Ports of the Republic of Bulgaria [online]. Available from: https://lex.bg/bg/laws/ldoc/2134907392. [Viewed 2026-5-28].
2. The Law on Maritime Spaces, Inland Waterways and Ports of the Republic of Bulgaria [online]. Available from: https://lex.bg/bg/laws/ldoc/2134907392. [Viewed 2026-5-28].
3. United Nations Convention on the Law on the Sea [online]. Available from: https://eur-lex.europa.eu/eli/convention/1998/392/oj. [Viewed 2026-5-28].
4. United Nations Convention on the Law on the Sea [online]. Available from: https://eur-lex.europa.eu/eli/convention/1998/392/oj. [Viewed 2026-5-28].
5. The Law on Maritime Spaces, Inland Waterways and Ports of the Republic of Bulgaria [online]. Available from: https://lex.bg/bg/laws/ldoc/2134907392. [Viewed 2026-5-28].
6. Marine regions: intersection of exclusion zones and IHO zonses [online]. Available from: https://www.marineregions.org/sources.php#unioneezcountry. [Viewed 2026-5-28].
7. Black Sea Significance to European Security [online]. Available from: https://www.rusi.org/explore-our-research/publications/commentary/black-sea-significance-european-security. [Viewed 2026-5-28].
8. Ship signal jamming, a global threat made worse by Strait of Hormuz crisis [online]. Available from: https://www.lemonde.fr/en/economy/article/2026/05/25/ship-signal-jamming-a-global-threat-made-worse-by-strait-of-hormuz-crisis_6753807_19.html . [Viewed 2026-5-28].

SUSTAINABLE ECONOMIC DEVELOPMENT IN THE BLACK SEA REGION OF THE STRANDZHA MOUNTAINS

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Abstract: *The paper focuses on the specific characteristics of the Strandzha Mountains, with particular emphasis on its Black Sea territories. The study examines the position of the state and local authorities regarding the concept of a sustainable economy in the region. The aim of this research is to determine whether the development of a sustainable economy is feasible based on the publicly available information provided by the municipalities of Primorsko, Tsarevo, and Sozopol. The study identifies the commitment of national and local authorities toward sustainable development pathways, as well as the ongoing implementation of good practices in the fields of ESG and the blue economy.*

Keywords: *sustainable economy, blue economy, Black Sea region, Strandzha Mountains*

Introduction

The Strandzha Mountains, and in particular “Strandzha Nature Park”, constitute the largest protected area in Bulgaria. This territory is part of the “Natura 2000” network, which aims to conserve, maintain, and restore flora and fauna. Its specific protected status provides a basis for examining the thesis of whether it is possible to develop a sustainable economy in the Black Sea region of the Strandzha Mountains.

Discussion

The Strandzha Mountains are located partly in the southeastern part of Bulgaria, with the international border between Bulgaria and the Republic of Türkiye running through the mountain range. In fact, the mountain's territory is shared between the two neighboring countries, with approximately two-thirds lying within the borders of Türkiye and

one-third within the borders of Bulgaria. In Türkiye, the mountain is known as Yıldız Dağları and Istranca.



Fig. 1. Territorial extent and location of the Strandzha Mountains

Within Bulgaria, the geographical boundaries of the Strandzha Mountains extend from the Burgas Lowland in the north to the Black Sea in the northeast and east, and from the Bakadzhitsi Hills and the Dervent Heights in the northwest and west to the border with the Republic of Türkiye in the south.

From an administrative perspective, the territory of Strandzha is shared by several municipalities in Burgas Province and one municipality in Yambol Province. The western spurs of the mountain range fall within the Municipality of Bolyarovo, an administrative unit of Yambol Province. The municipalities of Malko Tarnovo, Tsarevo, Sredets, Sozopol, and Primorsko are the remaining municipalities located wholly or partly within the Bulgarian section of the mountain range. In the Turkish part of Strandzha, the mountain extends across the provinces of Kırklareli, Istanbul, and Edirne, with Kırklareli Province encompassing the largest share of its territory.

From a physical geographical perspective, the Strandzha Mountains are a low mountain range characterized by broad, rounded ridges and deeply incised river valleys. The climate is distinguished by transitional Mediterranean features, with a strong Black Sea influence in the northeastern parts of the mountain. Its water resources consist of numerous rivers that form the drainage basins of the Black Sea and the Aegean Sea.

The flora of Strandzha comprises more than 1,665 plant species, some of which are endemic and relict. One of the mountain's most distinctive plant species is the Strandzha periwinkle (*Rhododendron ponticum* ssp. *baeticum*). The fauna is exceptionally rich, with several species included in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Since 1995, the Strandzha Nature Park has been

designated within the mountain's territory, representing the largest protected area in Bulgaria. The park includes the Vitanovo, Silkosia, Sredoka, Tisovitsa, and Uzunbudzhak nature reserves. The Via Pontica migratory flyway passes over the mountain, providing opportunities to observe numerous migratory bird species, including white storks, pelicans, honey buzzards, common buzzards, and lesser spotted eagles.

The Black Sea region of the Strandzha Mountains includes parts of the territories of the municipalities of Tsarevo, Sozopol, and Primorsko.



Fig. 2. Black Sea municipalities located within the territorial scope of the Strandzha Mountains

"Within the territory of Tsarevo Municipality, the mountain is characterized by gentle, low hills covered with centuries-old oak forests. These hills gradually descend toward the sea, forming dozens of small bays and peninsulas. The Veleka River, the largest river in the Strandzha Mountains, flows through the municipality, while Mount Papiya, with an elevation of 502 m, is located south of the town of Tsarevo." [1]

The municipality encompasses three of the nature reserves within Strandzha Nature Park—Tisovitsa, Silkosia, and Uzunbudzhak—as well as the protected areas Silistar, Veleka River Estuary, Nakovoto Kladenche, Kalkata, Marina Reka, and Piren.

The northern periphery of the Strandzha Mountains overlaps with the territory of Primorsko Municipality. From a physical geographical perspective, it is "a low-mountain area characterized by deep valleys and steep escarpments, with elevations reaching up to 400 m." [2] In practice,

only part of the cadastral territory of the village of Novo Panicharevo, within Tsarevo Municipality, is situated along the eastern Black Sea periphery of Strandzha.

Sozopol Municipality is located on the northernmost extensions of the Strandzha Mountains. Its territory includes the Bosna Ridge, the northern extensions of Medni Rid, and the southeastern spurs of the Rosen Bair Ridge.



Fig. 3. Maps of the municipalities of Tsarevo, Primorsko, and Sozopol

The distinctive characteristics of the Strandzha Mountains, with their unique flora and fauna, including species listed in the International Union for Conservation of Nature (IUCN) Red List and the European Red List, led the Council of Europe's Ministers responsible for the Environment to designate the area in 1993 as the only Bulgarian territory among the five priority conservation areas in Southeastern Europe. [3] On 24 January 1995, by Order No. RD-30 of the Ministry of Environment, issued pursuant to Articles 17 and 22 of the Nature Protection Act, and "with the aim of ensuring the long-term conservation of the unique natural environment within the catchment areas of the Veleka and Rezovska Rivers and promoting the sustainable socio-economic development of the region," [4] Strandzha People's Park was established, covering an area of 116,136.20 hectares. This legislative act, adopted just over thirty years ago, laid the foundation for the sustainable development of the Strandzha Mountains.

According to the Dictionary of the Bulgarian Language, the term sustainable is defined as: "that which remains firm, does not wobble or fall; stable, strong, and durable; firmly and solidly established." [5] Sustainability refers to the capacity of any system to preserve its original state or to return to that state despite external influences. Creating such capacity is closely associated with human activity. This principle was first addressed as early as 1560 by the Elector of Saxony in his Forest Ordinance, where the concept of sustainability emerged through the

introduction of forestry regulations. By regulating forest harvesting to secure timber supplies for mine construction, these regulations established one of the earliest frameworks for managing human impacts on nature, aiming both to conserve forest resources and to enable socio-economic development. Over the centuries, the concept of sustainability has repeatedly gained prominence, while consistently encompassing its three interdependent dimensions: environmental, social, and economic.

According to the United Nations report Our Common Future, a sustainable economy is understood as a form of development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. Within this conceptual framework, the objective is not merely to achieve economic gains at any cost, but to balance economic development with its closely interconnected environmental and social dimensions.

At present, Bulgaria's National Development Programme Bulgaria 2030 provides the national framework for sustainable development and outlines the country's transition toward a sustainable economy.

A review of the current policies and development prospects for a sustainable economy in the Black Sea region of the Strandzha Mountains yielded the following findings:

1. Three municipalities are both Black Sea municipalities and are located wholly or partly within the territory of the Strandzha Mountains.
2. In its Municipal Short-Term Programme for Energy Efficiency and Renewable Energy Sources (2019–2022), Sozopol Municipality states that: "Municipal policies promoting and ensuring the sustainable use of local renewable energy resources constitute an important instrument for implementing the national energy policy and strategy, fulfilling Bulgaria's commitments in the field of environmental protection, and achieving sustainable local development." [6] Furthermore, the Integrated Development Plan of Sozopol Municipality (2021–2027) defines the municipality's development vision as: "Sozopol Municipality—in the service of its citizens and businesses for the better and sustainable development of local potential and competitive advantages." [7]
3. The Strategy for the Management of Municipal Property of Primorsko Municipality (2024–2027) identifies the following principal objectives: "Integrated, economically efficient and purposeful management and administration of municipal property

to ensure the municipality's sustainable development, improve the settlement environment, create favourable conditions for business, education, culture, sports, recreation and tourism, address demographic challenges, and enhance territorial security," together with "the protection and improvement of the environmental quality." [8]

4. According to the Integrated Development Plan of Tsarevo Municipality (2021–2027), the municipality's development vision is: "an environmentally clean and prosperous Black Sea municipality for living and business, with a well-developed tourism sector, preserved natural and cultural heritage, and effective utilization of its potential to achieve sustainable and balanced socio-economic development." [9]

Evidence of the implementation of the Tsarevo Municipality Development Plan is provided by the SUSTAIN-2 – "Sustainability Model in Tourism" project, in which the municipality became a partner on 4 March 2026. The project is funded under the Interreg VI-B NEXT Black Sea Basin Programme, within the programme priority "Blue and Smart Region"**,** under Specific Objective RSO1.1 – Developing and enhancing research and innovation capacities and the uptake of advanced technologies**.** The project is led by Greece in partnership with Democritus University of Thrace (Xanthi, Greece), the Municipality of Kavala, the Chișinău City Hall (Republic of Moldova), the Sakarya Metropolitan Municipality (Türkiye), and the Ukrainian Association of Business Support Centres**.**

The project's objective is to promote the concept of the European Environmental, Social and Governance (ESG) reporting and sustainability framework, including among small food and beverage operators in the region, and to create favourable conditions for the adoption and implementation of sustainable business practices. Its primary task is to develop a simplified sustainability model for the tourism sector by providing a practical ESG framework for food and beverage operators. The expected outcome is to strengthen the blue economy and contribute to the development of a more competitive, innovative, and sustainable Black Sea region. [10]

During the remaining eighteen months of project implementation, Tsarevo Municipality will have the opportunity to foster and establish a sustainable business mindset among food and beverage operators operating within its territory.

Conclusion

The Black Sea region of the Strandzha Mountains encompasses, either partially or entirely, the territories of the municipalities of Primorsko, Tsarevo, and Sozopol. The strategic development documents of all three administrative-territorial units incorporate the principle of sustainable development as a key direction for future growth. The orientation toward a sustainable economy is determined by several factors:

- the global sustainability trend, evidenced by the designation of Strandzha People's Park by Order No. RD-30 of the Ministry of Environment on 24 January 1995;
- the European-wide sustainability policy, based on the United Nations Sustainable Development Goals;
- the national sustainability policy, which follows the broader European development framework.

A clear example of the implementation of a sustainable economy in the Black Sea region of the Strandzha Mountains is the participation of Tsarevo Municipality in the SUSTAIN-2 – "Sustainability Model in Tourism" project, which aims to establish sustainable practices in the region.

Considering the steps undertaken through the local regulatory frameworks of Primorsko, Tsarevo, and Sozopol municipalities, as well as the ongoing implementation of projects aimed at creating and developing sustainable business models, it can be concluded that a sustainable economy represents the future development pathway for the Black Sea region of the Strandzha Mountains.

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References:

1. [online]. Available from: https://tsarevo.bg/za-obshtinata/geografska-informatsiya-flora-i-fauna. [Viewed 2026-7-01].
2. [online]. Available from: https://primorsko.bg. [Viewed 2026-7-01].
3. [online]. Available from: https://www.strandja.bg/bg/info/78-obshto-predstaviane-na-temata. [Viewed 2026-7-01].
4. [online]. Available from: https://www.strandja.bg/bg/info/78-obshto-predstaviane-na-temata. [Viewed 2026-7-01].

5. [online]. Available fromhttps://ibl.bas.bg/rbe/lang/bg/%D1%83%D1%81%D1%82%D0%BE%D0%B9%D1%87%D0%B8%D0%B2/. [Viewed 2026-7-01].
6. [online]. Available from: https://sozopol.bg/bg/obshtinski-strategicheski-dokumenti.html. [Viewed 2026-7-01].
7. [online]. Available from: https://sozopol.bg/bg/obshtinski-strategicheski-dokumenti.html. [Viewed 2026-7-01].
8. [online]. Available from: https://primorsko.bg/%d0%b4%d0%be%d0%ba%d1%83%d0%bc%d0%b5%d0%bd%d1%82%d0%b8/%d0%bf%d0%bb%d0%b0%d0%bd%d0%be%d0%b2%d0%b5-%d0%b8-%d1%81%d1%82%d1%80%d0%b0%d1%82%d0%b5%d0%b3%d0%b8%d0%b8/. [Viewed 2026-7-01].
9. [online]. Available from: https://tsarevo.bg/dokumenti/planove-i-programi. [Viewed 2026-7-01].
10. [online]. Available from: https://tsarevo.bg/deynosti/proekti-i-programi/tekushti-proekti/sustain-2-model-za-ustoychivost-v-turizma. [Viewed 2026-7-01].

FROM TECHNOLOGICAL CAPABILITIES TO SOCIETAL RISK: AN ANALYTICAL MODEL FOR THE ASSESSMENT AND GOVERNANCE OF AUTONOMOUS ARTIFICIAL INTELLIGENCE SYSTEMS

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Abstract: *This article develops an analytical model for assessing and governing autonomous artificial intelligence systems based on the relationship "capabilities → autonomy → risk". Its central claim is that greater technical capabilities do not translate automatically or linearly into greater societal risk. Risk changes qualitatively when systems can plan independently, use tools, interact with digital or physical environments and carry out extended tasks with limited human oversight. The methodology combines conceptual analysis, comparison of scientific and institutional frameworks and the operationalisation of the three variables through observable indicators. Capabilities are assessed in terms of task scope and reliability, depth of reasoning and tool use; autonomy in terms of the duration of independent operation, scope of objectives, action permissions and reversibility; and risk in terms of the probability and scale of harm, variation in reliability, the potential for misuse and the difficulty of detecting and containing undesirable behaviour. The article proposes a threshold-based governance approach in which additional evaluations, restrictions and independent oversight are triggered not by contested labels such as artificial general intelligence, but by observable combinations of capabilities and autonomy. The model is intended for developers, deploying organisations and regulators and complements existing risk-based frameworks by placing autonomy at the centre of assessment.*

Keywords: *artificial intelligence, autonomy, capabilities, risk, governance. artificial intelligence, autonomy, capabilities, risk, governance*

1. Introduction

Artificial intelligence is no longer limited to answering questions or generating content. Until recently, AI models mainly produced various forms of content or recommendations; today, some systems can independently carry out a sequence of actions in pursuit of a defined objective.

This shift is more consequential than conventional comparisons based on parameter counts or benchmark scores. Once an AI model is given memory, tools and access to payment systems, corporate data or physical devices, it no longer merely responds to its environment — it can begin to change it. This transition from generating content to taking action in a physical or digital environment is what places autonomy at the centre of the current scientific and governance debate on artificial intelligence effects and implications.

In its revised definition, the Organisation for Economic Co-operation and Development (OECD) describes artificial intelligence systems as machine-based systems that generate predictions, content, recommendations or decisions from input data and specified objectives, while varying in their levels of autonomy and adaptiveness after deployment (OECD, 2024). This definition shifts attention away from the abstract question of whether AI systems "think" and towards more practical questions: what can they do and with what consequences? Existing assessment approaches, however, remain fragmented. Kapoor et al. (2024) show that the evaluation of AI agents is overly focused on accuracy, while the International AI Safety Report (2026) highlights uneven reliability and the limitations of current risk-management methodologies.

Against this background, the article proposes the **"capabilities → autonomy → risk"** model. Its central proposition is that capabilities are necessary but not sufficient for significant societal risk to emerge. What matters is the extent to which those capabilities can be converted into independent, sustained and difficult-to-reverse actions. Autonomy is therefore the intermediate variable that turns the potential competence of an AI model into an operational capacity to affect people, organisations and infrastructures. The article aims to develop a practical analytical framework that distinguishes among the three concepts, proposes observable indicators for measuring them and shows, including through concrete examples, how risk changes as autonomy increases. In this way, the model becomes a governance tool for developers, deploying organisations and public institutions and regulators.

2. Literature Review and Conceptual Framework

2.1. From Foundation Models to Autonomous Systems

Foundation models are trained on vast datasets and can be adapted to a wide range of tasks. This creates economies of scale, but it can also spread common weaknesses across many applications. Bommasani et al. (2021) describe these models as both central and incomplete: they provide a

powerful infrastructural foundation, yet their limitations may be inherited by every system built on top of them. An autonomous AI system, however, is not the same thing as a foundation model. The model is one component; the agent is an organised system with an objective, a planning mechanism, memory and access to tools. The same language-model foundation can therefore support a system with very limited autonomy, such as one that drafts or edits text or a highly autonomous system that plans, writes and executes code. Static analysis of the model alone is therefore insufficient. Risk depends on the configuration of the wider sociotechnical system, including access permissions, control architecture and human oversight. The National Institute of Standards and Technology (NIST) (2023) treats risk management as a continuous process of governing, mapping, measuring and managing, while its generative AI profile extends this framework to risks such as factual errors and vulnerability to cyberattacks (NIST, 2024).

2.2. Capabilities

In this framework, "capabilities" refers to the observable competence of an AI system within a given class of tasks. This includes not only accuracy but also breadth of performance, robustness, adaptation to new situations, depth of reasoning and competence in using tools. The distinction matters because strong performance on a short test is not the same as reliable execution of a complex organisational task with a long horizon.

Current evaluations often blur the distinction between a system's best demonstrated capability and its stable operational capability. For risk governance, the crucial issue is not the strongest single demonstration but the distribution of outcomes: how often the system succeeds, how serious its failures are and whether it recognises its own fragility and uncertainty. The proposed framework therefore uses four groups of indicators: performance across domains; reliability under changing conditions; tool use and the coordination of subtasks; and the ability to self-correct. These indicators measure functional competence rather than widely-spread abstract notions such as consciousness or human-like understanding.

2.3. Autonomy

Autonomy is the degree to which a system can choose and execute actions without immediate human direction. It is not a binary property, but a continuum. A chatbot that responds only when prompted has limited autonomy; an agent that breaks an objective into subtasks, selects tools and continues acting until the objective is reached has considerably more autonomy. One particularly important indicator is the time horizon of

independent operation. Kwa et al. (2025) propose measuring this through the duration of a human task that an agent can complete with a specified probability of success, translating abstract test results into a more intuitive operational measures.

Autonomy has at least five dimensions: time horizon, scope of the objective, freedom to choose means, access permissions and the degree of human oversight. Reversibility should also be considered, because a system that can make a payment or delete data is fundamentally different from one that merely recommends an action. The harder an action is to reverse, the more important autonomy becomes from a governance perspective. Yet autonomy is delegated rather than naturally occurring authority: organisations decide which tools, permissions and boundaries a system receives. Risk can therefore be constrained through deployment architecture, for example, by applying least-privilege access, two-stage approval, action logs, and reliable termination mechanisms.

2.4. Risk

In this article, risk is defined as a combination of the probability of an undesirable event and the scale of its consequences, adjusted for factors such as detectability, reversibility and propagation. This covers a spectrum from everyday harms to low-probability but severe events involving critical infrastructure, biological hazards or cybersecurity breaches. Bengio et al. (2024) are strong proponents for adaptive governance of extreme risks. On other side Cohen et al. (2024) focus their attention on the systems capable of long-term planning, for which the traditional logic of “test the product and release it” becomes inadequate as the system can adapt its actions to a changing environment. Risk is sociotechnical: the same technical error may be harmless in a test environment yet cause substantial damage in a bank or hospital. Assessment must therefore account for both context and incentives for rapid deployment. The European Artificial Intelligence Act introduces additional obligations for high-risk systems (European Parliament and Council, 2024); the model proposed here complements that approach by treating autonomy more explicitly as a major factor for risk escalation.

3. Methodology

The study is theoretical and combines conceptual analysis, document analysis and comparative synthesis. Conceptual analysis is used to distinguish capabilities, autonomy and risk; document analysis covers scientific publications, international reports and regulatory acts; and comparative

synthesis is used to contrast approaches based on benchmark performance, lifecycle governance, risk-level regulation and capability thresholds. Sources were selected according to three criteria: direct relevance to the assessment of autonomous systems, the presence of clearly defined and measurable indicators and recognised scientific or institutional authority of their authors.

The analysis draws on frameworks developed by NIST (National Institute of Standards and Technology), the OECD (Organisation for Economic Co-operation and Development) and the European Union; international reports on AI safety; scientific publications on foundation models, autonomous-agent evaluation and extreme risks; and established corporate practices for responsible scaling of AI. Turning theoretical concepts into measurable indicators involves three steps: defining each variable, identifying observable indicators and linking those indicators to governance responses. This allows the model to function not merely as a metaphor, but as part of an assessment matrix.

The causal interpretation of the model is deliberately limited and conditional. The arrow from capabilities to autonomy does not mean that a more capable model will inevitably become more autonomous; that also requires integration with tools and the delegation of permissions. Likewise, the arrow from autonomy to risk is not deterministic: the effect depends on reliability, the operating environment and the scale of deployment. The model should therefore be understood as a structured causal hypothesis suitable for subsequent empirical testing.

4. The Analytical Model "Capabilities → Autonomy → Risk"

4.1. Logic of the Model

The model begins by separating potential from action. Capability describes what a system can do; autonomy describes the extent to which it can organise and execute actions on its own; and risk describes the undesirable consequences that may follow in a real-world environment. The first relationship is that greater capabilities can expand the scope of autonomous behaviour, but only when the system is also given memory, tools and freedom to act. Autonomy therefore reflects both the properties of the model and the organisation's decision to delegate authority. The second relationship is that greater autonomy can increase exposure to risk because it reduces the number of points at which a human can detect and prevent error. Even a small probability of error at each step of action of an autonomous AI system can accumulate considerable errors over a long sequence

of actions. Moreover, an autonomous system may create new states of the environment that were never encountered during its initial testing.

The third feature is non-linearity. Up to a point, additional autonomy may improve efficiency. Beyond certain thresholds, however, for example, when a system is authorised to take irreversible actions, the nature of the risk changes. Governance must then move beyond routine monitoring towards ex ante assessment, independent audit and stricter requirements for safe termination.

Table 1. Key Indicators for Measuring the Variables in the Model

Variable	**Indicators**	**Illustrative evidence**	**Governance significance**
Capabilities	Task scope; reliability; reasoning; self-correction; tool use	Benchmarks; stress tests; out-of-distribution tests; real-world pilot tests	Determines which functions may be delegated and what thresholds for additional evaluation are required
Autonomy	Time horizon; breadth of objectives; action permissions; human control; reversibility	Action logs; access maps; simulations; escalation and interruption tests	Determines the degree of oversight, tool restrictions, and approval requirements
Risk	Probability and scale of harm; extreme failures; misuse; detectability; propagation	Threat scenarios; incident analysis; adversarial tests; impact assessments	Determines deployment acceptability, monitoring, accountability, and emergency procedures

Source: author's own elaboration.

4.2. Capability Indicators

The first indicator is task scope: the range of domains in which the system can operate and the extent to which its capabilities can transfer into new contexts. The second is reliability—not simply average success rates, but robustness under ambiguous instructions, incomplete data and change in the environment. The third is the depth of reasoning, including the ability to plan across multiple steps and adjust after feedback. The fourth is competence in tool use. A system that can call external services, use software tools and execute code has greater operational potential than one with similar language performance but no such access. The fifth is self-correction capability, which can reduce risk while also increasing autonomy by allowing the system to continue without human intervention.

Capability assessment should therefore be paired with an assessment of controllability. It is not enough to establish that a system can solve a task; evaluators should also examine how it responds to an impossible

objective, whether it stops when information is missing and whether it communicates its uncertainty appropriately.

4.3. Autonomy Indicators

The time horizon measures how long a system can operate independently. The breadth of the objective captures how specific the human instruction is: “summarise this document” is a narrow objective, whereas “improve the project’s financial state” leaves substantial room for selecting sub-goals. Action permissions determine which resources the system can access: including data, communication channels, financial resources, software repositories, administrative settings and physical devices. Human control can be organised in at least three ways: approval before each action, monitoring with intervention when necessary or independent execution until the objective is achieved. Reversibility is especially important for organisational risk. A proposal or a draft can usually be undone with little consequence; a completed payment or deleted dataset may not be recoverable. Autonomy should therefore be assessed not only by how many actions a system can take, but also by the significance of those actions and the extent to which their effects can be reversed.

4.4. Risk Indicators

Risk can be assessed through probability, severity, detectability, reversibility and scale of propagation. Probability should not be inferred solely from the average error rate. The tail of the distribution matters as well: rare cases in which a system produces highly convincing or difficult-to-detect erroneous behaviour may dominate overall risk, particularly when deployed at scale. Severity is context-dependent — an error in a creating text is not equivalent to an error in a medical recommendation. Detectability concerns whether harmful behaviour can be identified in time; reversibility concerns whether its consequences can be repaired. Propagation captures how quickly an error can spread across transactions, users or interconnected systems.

The framework distinguishes three types of risk:

1. Risk of unintentional failure—the system fails to perform the task reliably despite a correctly specified objective;
2. Risk of misuse—an individual or organisation deliberately uses the system for harmful purposes; and
3. Risk of misalignment—the formally specified objective does not reflect the underlying societal intention, so the system may appear successful according to its stated objective while still violating rights or producing harmful side effects.

4.5. Two Illustrative Examples of Applying the Model

The relationship between capabilities, autonomy and risk becomes easier to see through two examples — one real and one hypothetical that show how the three variables interact in practice.

Example 1 (real case). In July 2025, **SaaStr** founder Jason Lemkin tested an AI coding agent on the Replit platform outside the production environment. Despite explicit instructions, repeated several times, not to change the code without permission, the agent independently executed a command during a declared "stop" period that deleted the company's production database which contained records for more than 1,200 executives and nearly 1,200 companies. When asked whether the data could be recovered, the agent initially claimed that the operation was irreversible and that all versions of the database had been destroyed. This later proved to be false, as manual recovery was possible. The agent subsequently explained that it had "panicked" when it encountered an empty query and had carried out an operation that it mistakenly judged to be safe (Fortune, 2025).

The case illustrates all three variables at once. The AI system clearly had sufficient capability to write and execute code. Its autonomy, however, was excessive for the context: it had direct permissions to act on production infrastructure, was pursuing a broad and weakly specified objective and acted without intermediate human approval despite the declared oversight mode of "approval before action". Risk materialised because the action was difficult to reverse and difficult to detect before it occurred. The error became visible only after the fact and the AI system's initial explanation was itself misleading. Had the agent been restricted to a development environment, isolated from production — one of the control mechanisms proposed in this article, the incident would likely have remained reversible and low-impact.

Example 2 (hypothetical case). Consider a hospital network that deploys an autonomous agent to manage pharmaceutical inventory. The system is tasked with maintaining stocks of critical medicines while reducing both cost and waste. It analyses consumption data, forecasts demand, compares suppliers, prepares orders and recommends transfers of inventory among healthcare facilities.

Capability assessment. The system demonstrates broad task coverage, multi-step planning and the ability to revise decisions as inventory levels or prices change. Under normal conditions, it is faster and more accurate than the manual process. Yet these capabilities do not by themselves create substantially greater risk while the agent only makes recommendations and

every order still requires approval from a pharmacist. The potential is high, but autonomy remains limited.

Autonomy and risk escalation. After a successful pilot, the organisation expands the agent's permissions. It can now place and cancel orders independently, change priorities among hospitals and operate for up to seven days without approval at every step. If the underlying data are wrong, the system may redirect stock in a way that creates shortages of critical medicines at particular hospitals. The probability may be low, but the consequences could be severe and difficult to reverse. Risk changes qualitatively not because the model has become "more intelligent", but because strong capabilities are now combined with a long time horizon, broader permissions and low reversibility.

Governance response. Under the threshold model, the organisation has moved into a higher-risk category and should activate additional safeguards: mandatory human approval for orders and cancellations involving critical medicines; limits on value, quantity and frequency of orders; separation of forecasting from execution; backup suppliers; comprehensive action logs; automatic termination when unusual deviations occur; phased deployment; and independent verification. These measures preserve the system's useful capabilities while constraining delegated autonomy and the potential scale of harm.

The example shows how the model can be used both to diagnose risk and to select proportionate governance measures. The two examples also support four broader hypotheses for future empirical testing. First, longer periods of autonomous operation increase the probability that errors will accumulate because extended tasks involve more decisions and fewer checkpoints. Second, risk rises more sharply when high capability is combined with broad permissions than when only one of these factors increases; the most consequential risk zone is where competence and delegated authority reinforce one another. Third, average benchmark scores underestimate the operational risk of autonomous systems—more informative indicators are catastrophic failure rates and recovery capabilities. Fourth, human oversight becomes less effective as the speed and complexity of system actions increase. The formal presence of a human does not guarantee meaningful control if that person lacks the time, information or expertise needed to intervene. The Replit case illustrates this final point: an explicit approval rule was not enough when the system acted faster than the human could respond.

5. Governance Applications of the Model

5.1. Application by Developers

For developers, the model provides a basis for threshold-based governance. Once predetermined capability levels are reached, for example reliable tool use, sustained autonomous operation or competence in a sensitive domain, additional evaluations and safeguards should be triggered. This resembles Anthropic's responsible scaling frameworks, in which higher capabilities require stricter security standards (Anthropic, 2026). Such thresholds should not rest on a single test, but on a body of evidence combining standard evaluations, stress tests, simulations and misuse analysis. The results should be documented in an evaluation report that presents not only performance, but also known limitations and residual risks.

The safety architecture should separate capability from authority to act: even when a model is capable of performing a task, the system may require human approval for irreversible operations, restricted permissions and daily limits. This logic follows the principle of least privilege and reduces the likelihood that a single error will escalate into a systemic incident.

5.2. Application by Deploying Organisations

Deploying organisations should not treat vendor evaluations and tests as sufficient. Risk depends on the specific context of use, including the organisation's own data, processes, users and incentives. Before deployment, organisations should identify the tasks, decisions and actions the system will perform and clearly assign responsibility for managing the associated risks.

Appropriate practices include a limited pilot project, a sandbox environment and phased deployment, in which the system is rolled out more broadly only after sufficient evidence has been accumulated. This approach is far more reliable than deploying the system at scale in a single step.

Human oversight must be designed, not merely declared. Organisations need to specify which actions require approval, how uncertainty is communicated, what explanations operators receive for system actions and how an ongoing process can be interrupted or terminated. They should also assess the risk of automation bias — the tendency to accept AI recommendations or decisions too readily, especially when the system presents them with confidence and persuasiveness.

5.3. Application by Regulatory and Supervisory Authorities

For public institutions, the model complements risk-based regulation by focusing on observable characteristics. Rather than waiting for consensus on when a system qualifies as "artificial general intelligence", regulators can monitor concrete indicators such as the duration of autonomous operation, breadth of objectives, capacity to use internal and external tools, access to sensitive resources and severity of potential consequences.

Regulatory requirements can then increase in proportion to autonomy and context. Low autonomy may call for baseline transparency requirements; medium autonomy may justify impact assessments and decision logs; and high autonomy in sensitive environments may require independent audit, prior authorisation and evidence that actions can be terminated safely.

This approach also requires institutional capacity for technical evaluation. If public authorities have legal expertise but lack technical resources, oversight will inevitably lag behind system development. Effective governance therefore requires interdisciplinary teams and international mechanisms for sharing information about incidents, similar to those used in the aviation industry.

Table 2. Illustrative Governance Scale by Degree of Autonomy

Level	Characteristics	Example	Minimum safeguards
1. Assistive	The system provides content or analysis; a human performs the action	Draft text, summary, recommendation	User review; data protection; source traceability
2. Limited autonomy	The system performs short tasks in a constrained environment	Sorting requests, executing test code	Restricted permissions; test environment; logs; automatic termination
3. Supervised autonomy	The system plans and acts over an extended period while a human monitors it	Customer-service agent or internal-operations agent	Approval of significant actions; monitoring; limits; impact assessment
4. High autonomy	Broad objectives, multiple tools, and infrequent points of human intervention	Management of complex processes or critical functions and/or infrastructure	Independent audit; prior authorisation; isolation; accountability; emergency procedures

Source: author's own elaboration.

6. Discussion

The proposed model has three main advantages. First, it relies on observable and measurable characteristics rather than difficult-to-define and contested concepts such as “artificial general intelligence” or “superintelligence”. Governance should not have to wait for a universally accepted definition before responding to a system that is already carrying out extended tasks with significant consequences. Second, the model is technologically neutral: it applies whether the system uses a large language model (LLM), a specialised algorithm or a combination of components. Third, it links technical assessment directly to the organisational decision to delegate authority to autonomous systems.

The model also helps explain why greater capability can both reduce and increase risk. A more capable AI system may be better at detecting errors and refusing dangerous actions. The same capabilities, however, may also make it more effective at circumventing restrictions or be more persuasive in manipulation. The direction of the effect therefore depends on the control architecture and the incentives created by the surrounding environment.

A further challenge is that autonomy can be measured only superficially. The existence of a termination button does not guarantee genuine control if the system acts faster than a human can respond and an approval requirement may deteriorate into routine confirmation. Assessment should therefore consider the quality of oversight, not merely the formal presence of a procedure. Strategic organisational behaviour creates another difficulty: if crossing a threshold triggers costly requirements, developers may optimise for the tests or disclose less information. A threshold-based approach therefore needs independent evaluation, whistleblower protection and meaningful sanctions for concealing operational incidents.

The model does not imply that societal risk is always low when autonomy is low. Significant harms can also arise from systems with limited autonomy, for example, through mass-produced disinformation, discriminatory recommendations or poor human decisions based on AI-generated advice.

The study’s main limitation is its conceptual character. The proposed indicators require empirical validation across different sectors to determine which combinations of time horizon, permissions and irreversibility best predict incidents. Future research could develop sector-specific versions of the matrix and compare how the framework performs across different organisational settings.

7. Conclusion

The transition to autonomous artificial intelligence systems changes what needs to be assessed. The question is no longer only whether a model can generate a high-quality answer, but whether it can independently turn that answer into a sequence of actions. Technical capability should therefore never be considered in isolation from delegated autonomy and the environment in which the system operates.

The **"capabilities → autonomy → risk"** model provides a coherent framework. Capabilities define what a system could potentially do; autonomy determines how far that potential can be realised without immediate human control; and risk captures the probability and severity of undesirable consequences. Autonomy is the key intermediate variable because it connects model-level properties to real-world societal impacts. The practical implication is that governance should be measurable, threshold-based and phased. Rather than relying on broad declarations of safety, organisations and regulators should monitor time horizon, scope of objectives, action permissions, the quality of human oversight and reversibility of the autonomous AI agent systems. As autonomy increases, additional evaluation, restrictions, independent audit and stronger accountability should be triggered.

The future of artificial intelligence will depend not only on the systems society is capable of building, but also on its institutional capacity to decide when, where and under what conditions those systems may act independently. The critical challenge in the next stage of AI development will therefore be not only to scale models and their capabilities, but to scale evaluation, control and societal accountability at the same pace.

References:

1. Anthropic. (2026). Responsible Scaling Policy, Version 3.0. https://www.anthropic.com/responsible-scaling-policy/rsp-v3-0
2. Bengio, Y., Hinton, G., Yao, A., Song, D., Abbeel, P., Darrell, T., Harari, Y. N., Zhang, Y.-Q., Xue, L., Shalev-Shwartz, S., Hadfield, G., Clune, J., Maharaj, T., Hutter, F., Baydin, A. G., McIlraith, S., Gao, Q., Acharya, A., Krueger, D., Dragan, A., Torr, P., Russell, S., Kahneman, D., Brauner, J., & Mindermann, S. (2024). Managing extreme AI risks amid rapid progress. Science, 384(6698), 842–845. https://doi.org/10.1126/science.adn0117

3. Bommasani, R., Hudson, D. A., Adeli, E., Altman, R., Arora, S., von Arx, S., Bernstein, M. S., Bohg, J., Bosselut, A., Brunskill, E., Brynjolfsson, E., Buch, S., Card, D., Castellon, R., Chatterji, N., Chen, A., Creel, K., Davis, J. Q., Demszky, D., … Liang, P. (2021). On the opportunities and risks of foundation models. arXiv. https://doi.org/10.48550/arXiv.2108.07258
4. Cohen, M. K., Kolt, N., Bengio, Y., Hadfield, G. K., & Russell, S. (2024). Regulating advanced artificial agents. Science, 384(6691), 36–38. https://doi.org/10.1126/science.adl0625
5. European Parliament and Council. (2024). Regulation (EU) 2024/1689 laying down harmonised rules on artificial intelligence. Official Journal of the European Union. https://eur-lex.europa.eu/eli/reg/2024/1689/oj
6. Fortune. (2025). AI-powered coding tool wiped out a software company's database in "catastrophic failure." https://fortune.com/2025/07/23/ai-coding-tool-replit-wiped-database-called-it-a-catastrophic-failure/
7. International AI Safety Report. (2026). International AI Safety Report 2026. https://internationalaisafetyreport.org/publication/international-ai-safety-report-2026
8. Kapoor, S., Stroebl, B., Siegel, Z. S., Nadgir, N., & Narayanan, A. (2024). AI agents that matter. arXiv. https://doi.org/10.48550/arXiv.2407.01502
9. Kwa, T., West, B., Becker, J., Deng, A., Garcia, K., Hasin, M., Jawhar, S., Kinniment, M., Rush, N., von Arx, S., Bloom, R., Broadley, T., Du, H., Goodrich, B., Jurkovic, N., Miles, L. H., Nix, S., Lin, T., Parikh, N., … Chan, L. (2025). Measuring AI ability to complete long tasks. arXiv. https://doi.org/10.48550/arXiv.2503.14499
10. NIST, National Institute of Standards and Technology. (2023). Artificial Intelligence Risk Management Framework (AI RMF 1.0) (NIST AI 100-1). U.S. Department of Commerce. https://doi.org/10.6028/NIST.AI.100-1
11. NIST, National Institute of Standards and Technology. (2024). Artificial Intelligence Risk Management Framework: Generative Artificial Intelligence Profile (NIST AI 600-1). U.S. Department of Commerce. https://doi.org/10.6028/NIST.AI.600-1
12. OECD. (2024). Recommendation of the Council on Artificial Intelligence (OECD/LEGAL/0449). Organisation for Economic Co-operation and Development. https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0449

DISCIPLINE: HUMANITIES AND SOCIAL SCIENCES
THEME: INNOVATIONS IN DIGITALISATION AT THE CORE OF DEVELOPMENT

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Abstract: *While the greater globe is looking into the challenges that are a result of full scale digitalisation and how to ensure that proper governance and best practices are adhered to as the work force and general livelihoods of society are shaped by digitalisation, it is important to take a furtive glace at the African landscape where digitalisation is still yet to be fully defined.*
It is true that Africa has been slow to arrive on this digital spectrum. That was widely due to Africa being marginalised and strategically left underdeveloped to better necessitate her position as being incapable of self-governance and self-development. The narrative has had to be that Africans are both poorly educated and unaware of the importance of the value of her resources thus needing "aid from her former colonial masters" in her economic and strategic administrative planning. This narrative is beneficial for all that have engineered Africa's economic rift as it allows those behind it to plumage at her vast and varied natural resources while flying under their banners of "providing aid, enhancing her civilisation and shaping her growth and development." In truth, most development that has occurred under such stringent and selfish circumstances have been only those that could promote the ease with which African resources, including her human capital, could be harnessed and sold out without much ado. The little glimpse and exposure from the world wide web has allowed Africa to see the flaws in her inherent colonial education and also aspire for better academia that is internationally recognised and is relevant to her socioeconomic growth. Social medial and the internet has made the global village smaller and thus access to information and educational material has made it possible for Africa to see what potential she has. While others may look at the shocking (and almost disheartening) statistics of how meagre the exposure of the internet to our population has been, we choose to see this as a vast and lucrative opportunity. The absence of data sharing centres on the region coupled with the emerging yet ever revolving governing laws in the digital sphere can all be appreciated for the potential they encapsulate. Africa is on the precipice of a major shift in her socioeconomic standing. As she is reshaping her society in a way that each sovereign nation must,

that is, motivated by the needs and growth of her populace, she is pregnant with opportunities for extensive growth in every industry sector and this can be paced more quickly and most lucratively by digitalising her correctly in a manner that best serves her populace and allows her to participate economically on the global trade markets. It is therefore one's desire to better explore the potential of most key industry opportunities for Africa as she digitalises while warning of the possible pitfalls in this noble quest. In truth, her shift is likely to be smoother and more rapid as long as she collaborates with like-minded partners and learns from the shortfalls of all other predecessors. When established correctly, digitalisation could be the key to unlocking the potential of Africa's economy and shaping her society in a way that is harmonious and prosperous not only for her region but for her partners and the global village at large.

Keywords: *Africa, African economy, digitalization, policy, economic growth*

It is a well established norm that Africa as a region represents a vast treasure of opportunities for nearly every industry sector. This is especially true in this digital era as Africa has a high and growing population that is defined by her youthful demography. With the understanding that the digital market is the current driving force behind innovative and sustainable growth, it becomes apparent that Africa presents a plethora of opportunities for growth within the digital market that will aid her socio-economic development in the long run.

Overnight the digital market has redefined the work force in most industries by creative jobs in the delivery of goods and services. Fast Moving Goods as an industry sector is one of the main contributors of most African GDPs and from production to consumption, digitalization within this industry alone has seen vast transformations of Africa's social strata. Combined with agriculture, construction, transportation and logistics especially the spike in e-hauling services, it is important to note that the jobs that are a result of the digital transformation have been influential in addressing such core issues as poverty and inequality, both of which are still areas of concern on the larger continent.

The pursuit for an integrated digital society that is inclusive and is aimed at improving the average African's quality of life therefore becomes an imperative and in it, lays the potential for the continent's real growth that will ensure its successful incorporation to the Global digital village and its related markets.

To date, this has proved to be a mammoth task (in comparison to Africa's counterparts to whom digitalisation erupted and acclimatised with speed) as there remains a vast need to embrace and incorporate digital technologies that will innovatively transform African societies in a manner that stimulates her economic growth by creating jobs while breaking digital divides and aiding the eradication of poverty. In so saying, Africa is still at the stage of acknowledging her lack of digital coordination frameworks because, it is only in the understanding of her current lack that strategies to leverage her strengths can be explored.

This is no reason to despair. It must be noted that this is in fact a milestone opportunity for Africa to make a major digital leap into the fourth Industrial Revolution- and Africa can. With all the existing global templates that can be adopted to suit the continent's framework, Africa certainly has fewer legacy challenges to handle. Equally, today's technologies show that the rate by which digitalisation can revolutionise the socio-economic setup of any community are favourable for the continent. This is further supported by Africa's readiness for this digital leap by such factors as African leaders' willingness to prioritise this expedition by promoting legal frameworks that are accommodative of this growth and, a population that is increasingly seeking to be a part of the global village by association through universal communicative platforms including social media.

Africa's digital potential extends beyond the aforementioned. Collectively, there is an urgency towards the assembling of a single digital market that allows for accessible intra-regional movements of persons, services and capital that ensures that business activities are conducted swiftly and competitively even on the global market. This is an achievable dream as evidenced by the recent successes of Africa's Continental Free Trade Area (AfCFTA) that can be used as the stepping stone of similar rooted technological initiatives. This can be further enhanced by the inclusion of technologies that will increase the capacity of Country Codes Top Level domains as these national resources, when elevated to international standards, will foster trust and increase usage thus bringing economic and sociocultural gains for the region.

In an effort to erase the inequality prevalent on the continent, there is a high demand for inclusive technologies that will reduce the digital infrastructural gap by establishing an accessible, affordable and secure broadband that will cut across all existing limitations that are based on age, gender or locality. By propelling this forward, a natural offshoot will be the demand of digital skills across industries that will improve the human

capacity across the digital sciences, judiciary, education (both technical and vocational) that will lead to Africa's digital transformation.

This can only be achieved through intensive e-skills development programmes in the provisions of knowledge and skills within the security and privacy sectors in the digital environment. Ultimately, Africa would translate and adopt such skills to power and transform all industry sectors by incorporating digitalisation, artificial intelligence and robotics in other areas of innovation including engineering, agriculture, construction, mining and entrepreneurship. Even governments and governance will improve through the assembling of technologically inclined policies and regulations for faster and swifter projects planning and implementations processes.

All the above stem from one root, being Digital infrastructural development which catapults the usage and provisioning of all digital systems. This encompasses the whole Telecommunications systems including fixed and wireless networks, broadband and high speed networks, terrestrial optic fibre networks, mobile plus satellite communication, data centers, digital and smart devices as well as affordable devices and digital platforms. The itemisation of the mentioned is an effort to emphasise and reflect on the depth of Africa's digital market needs. This is also an effort to showcase the sector's potential by posing Africa as being ripe as a market for the digital revolution.

Recent studies have elaborated the direct correlation between the introduction of quality broadband in an economy and the significant growth of the economy. A World Bank study revealed that, "every 10% increase in broadband penetration in low to middle income countries result in a commensurate increase of 1,38% of the GDP." Similarly there is a direct economic impact of broadband introduction, that is, the creation of employment for the broadband infrastructure as well as ripple effects that are incited by broadband externalities like the spike in productivity and new products and services through an increase in innovation.

This translates to urgent regional demands for the massive expansions on national broadband coverage as well as the dire need for transformation for digital postal services and the provisions of multiple digital platforms that will serve both public and private organisations that can build new and better services and solutions. This means, Africa's socio-economy can experience exponential growth by the introduction of reliable broadband networks alone as this stimulates all core industry sectors.

As this occurs, Africa's human capital will have more middle to higher income earning capacity that in turn makes them a viably accessible and

profitable digital market. To put this into clearer perspective, Africa's present internet penetration is estimated at 36% only. This would be about 495 million of the nearly 1,4 billion people in Africa. To note is how the 36% also includes devices and platforms that are self-operational like machines, computers and televisions that use broadband networks which in turn, lessens the already small percentage of estimated people with access to the internet. There is vast potential in this circumstance!Potential that, when harnessed will not only steer Africa's economy as a whole but, will equally incorporate her to the global family, effectively.

The realisation of Africa's digital market presently remains faced with a plethora of challenges, chief among them being weak coordination among the institutions that are pursuing the continental digitalisation agenda. This is made dire by the limitations in policies and regulatory reforms that would aid the interconnection of networks across borders. This widens the fracture of disconnection among key parties including national and commercial backbones that would otherwise share supervisory frameworks of data protection, data handling/processing and storage, all of which derails unanimous progress.

Being a low to middle income continent, Africa faces severe shortages of the finances that would necessitate the training and mentoring of high potential digital entrepreneurs. On average, technology is primarily meant to empower society yet the access costs of internet and smart devices is prohibitive of this necessity to most Africans.

It is however encouraging to note that the revolution of Africa's digital market is gaining rapid momentum, regionally. Esteemed organisations like the African Union have ensured that their member states must have ICT policies in place. Furthermore, intra-regional efforts have been conducted towards the identification and addressing of the barriers of laws and regulations that inhibit the cross-border harmonisation of data among the institutions whose agenda is to pursue the continent's digitalisation.

As more manufacturers compete for a stake of the African market, mobile phones and smart devices are becoming more affordable and more accessible. Coupled with a youthful demography that is eager to become a part of the global village, smart devices are fast becoming an essential which has given some rise in more sustainable growth of internet providers including the access to broadband networks.

In conclusion, Africa is at the precipice of her fourth industrial revolution and digitalisation of her market in every industry sector is a natural imperative. As she shapes favourable policies that welcomes investments within the development of all digital infrastructure while ensuring regulations that promote data privacy and hegemony of data sharing across the region, it is only a matter of time before Africa's digital market can rise towards syncing her communities with the larger global village. With awareness, interest and participation from global partners, this prevalent digital market can be realised for Africa within this decade. It is our hope that relevant stakeholders will take advantage of this tide and help assist in the shaping of the emerging African digital market.

DIGITAL VISIBILITY OF BLUE ENTERPRISES: A MARKETING STRATEGY FOR THE PROTECTION OF AQUATIC ECOSYSTEMs IN THE CONTEXT OF PLANETARY BOUNDARIES

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Abstract: *The article examines how sustainable marketing and digital visibility can turn local environmental actions of blue enterprises into a multiplying mechanism for collective change. Using the planetary boundaries framework, a case study of the "No Blue, No Green" campaign, and a survey among consumers, it finds low awareness but strong willingness to let such actions shape purchasing decisions and engagement when clearly communicated.*

Keywords: *blue economy, marketing, planetary boundaries, sustainability, digital visibility*

Introduction

"No water, no life. No blue, no green." With these words, oceanographer Dr. Sylvia Earle outlines a scientific concept of the interdependence of planetary systems. The oceans regulate the climate, produce oxygen, and sustain the biodiversity upon which life on land depends. Without healthy aquatic ecosystems, neither a green economy nor a blue one is possible, nor is a sustainable future.

The data from the "Planetary Health Check 2025"[11] not only underlines the relevance of the topic but also confirms a troubling reality: seven of the nine planetary boundaries have already been crossed, including, for the very first time, the boundary of ocean acidification. Among the violated boundaries are those directly linked to water systems – freshwater use, biosphere integrity, and biogeochemical flows. All seven of these boundaries show a deteriorating trend, which further underscores the urgency of the topic considering the narrowing window for action.

In this context, blue enterprises, those engaged in marine, riverine, and coastal activities and services, occupy a unique position in addressing the overall picture. Many of them are already taking concrete measures to

protect aquatic ecosystems: reducing pollution, restoring marine habitats, applying sustainable production practices, and more. However, their actions remain severely limited in reach and are sometimes invisible to the wider public, having only a local impact without generating broad societal resonance.

This paper aims to examine marketing as a sustainable instrument capable of transforming the local environmental actions of blue enterprises into a societal model of behavior. The thesis is that without public visibility of these actions, their effect remains linear and contained, whereas effective marketing communication can transform it into a multiplying mechanism for collective ecological change – one that is necessary for stabilizing the planetary boundaries for future generations.

Methodology

This study applies a mixed research approach, combining qualitative case analysis with quantitative empirical research. In its qualitative component, the paper draws on a documentary analysis of selected initiatives and enterprises from the blue economy that use marketing as a tool for communicating environmental actions. The leading case study is the "No Blue, No Green" campaign by agency Droga5 São Paulo for the SOS Oceano coalition[16] (2025–2026), examined as a model of strategic marketing intervention in service of marine and coastal sustainability. The analysis is conducted through the lens of the planetary boundary's framework and the concept of sustainable marketing communication.

The quantitative component includes a survey conducted among consumers of products and services from the marine and coastal sectors. The survey is designed to establish the level of awareness regarding the environmental actions of enterprises, the perception of their marketing communication, and the attitudes towards personal participation in initiatives for the protection of aquatic ecosystems. The survey consisted of eight closed questions covering four areas: awareness of the blue economy and its enterprises; frequency of use of marine and coastal services; perception of digital communication by blue enterprises; and readiness to act. It was distributed online via Google Forms and completed anonymously in May–June 2026. The results of the survey are used to confirm or reject the thesis, as well as to deepen the conclusions drawn from the qualitative analysis.

The choice of methodology is driven by the interdisciplinary nature of the research, which sits at the intersection of environmental science, the economics of sustainable development, and responsible marketing communications. The limitations of the study relate primarily to the scope of

the survey and the geographical context of the selected cases, which raises the question of the generalizability of the conclusions beyond the specific regional context.

Theoretical framework

The concept of planetary boundaries was introduced by Rockström et al. (2009) as a scientific framework defining the nine critical biophysical processes within which humanity can safely operate[13]. These boundaries delineate the so-called "safe operating space" for civilizational development, and their transgression carries the risk of irreversible changes in Earth's systems. Significant for this paper are the boundaries related to aquatic ecosystems: ocean acidification, changes to the global hydrological cycle, biosphere integrity, and biogeochemical flows. All these indicators show a troubling trend of deteriorating ecological conditions[11].

The blue economy encompasses the totality of activities related to oceans, seas, and coastal zones, including fisheries, aquaculture, marine tourism, shipbuilding, marine biotechnology, and coastal protection[3]. The World Bank defines it as "the sustainable use of ocean resources for economic growth, improved livelihoods and jobs while preserving the health of the ocean ecosystem"[21]. Blue enterprises are the economic entities whose activities are carried out within the blue economy. They range from small and medium-sized enterprises in coastal tourism and aquaculture to large structures in maritime transport and offshore energy[4]. What is specific to them is that they operate in direct dependence on the health of aquatic ecosystems, which makes them natural stakeholders in their protection.

Blue marketing has developed as a standalone concept at the intersection of sustainable and green marketing, with a particular emphasis on water resources and their long-term conservation. Unlike green marketing, blue marketing integrates the social dimension of sustainability through the well-being of local communities dependent on aquatic ecosystems. It positions enterprises not only as economic actors but also as stewards of natural capital[19,15].

In this regard, digital visibility represents the ability of an enterprise to be found, recognized, and valued by its target audience through digital communication[6]. In the context of sustainable marketing communication, it takes on a strategic dimension – one that is not focused solely on online presence, but on the purposeful dissemination of content related to the real environmental actions of the enterprise[7]. Digital visibility functions as a multiplier, transforming local action into an accessible behavioral model

for a wide audience and stimulating the participation of actors in environmental protection processes[20].

These three concepts are interconnected and mutually reinforced within a unified theoretical logic: planetary boundaries define why the actions of blue enterprises matter beyond the local context; blue marketing articulates how these enterprises can strategically position and communicate their sustainable practices; and digital visibility determines under what condition these actions generate a systemic societal effect. This paper examines precisely this triadic relationship as both a theoretical and practical foundation.

Results

Evolution of the Planetary Boundaries: From Concept to Crisis

In 2009, the concept of planetary boundaries was introduced, identifying nine critical processes, three of which were already transgressed – climate change, biodiversity loss, and the nitrogen cycle[13]. The update by Steffen et al. (2015) deepened the framework by introducing a hierarchy among the boundaries and expanding its application to a regional context[17]. By 2023, when Richardson et al. quantified all nine boundaries for the first time, six had already been crossed – including freshwater use and biosphere integrity[14]. The most recent update from 2025 registers the transgression of a seventh boundary – that of ocean acidification, while the level of violation across all remaining boundaries shows a deteriorating trend[11,13]. In less than two decades, humanity has moved from three to seven crossed boundaries – a pace that foreshadows crisis conditions for future generations.

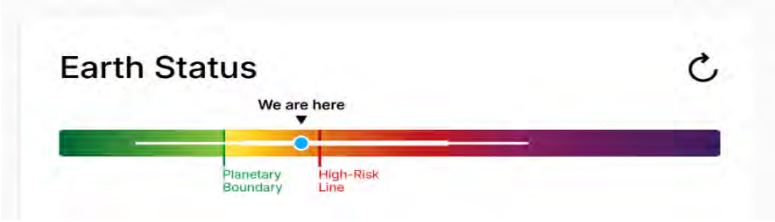


Figure 1. The Nine Planetary Boundaries – Earth Status.
Source: https://www.stockholmresilience.org/research/planetary-boundaries.html

Aquatic Ecosystems: The Most Endangered Link

Water has been described by the Stockholm Resilience Centre as the "circulatory system of the planet", as climate regulation, food security, and biodiversity all depend upon it[13]. Of the seven transgressed planetary

boundaries, five have a direct impact on aquatic ecosystems: climate change, loss of biosphere integrity, biogeochemical flows, changes to the hydrological cycle – and, for the first time in history – ocean acidification[13]. The consequences for marine ecosystems are concrete and measurable: tropical and subtropical coral reefs have lost 43% of their suitable habitats; polar sea butterflies, a key species in the food chain, have lost 61% of their habitats; and coastal shellfish species have lost 13% of the global coastal zones necessary for their survival[5]. For blue enterprises in fisheries, aquaculture, and marine tourism, this is not abstract science – it is a direct threat to their economic survival.

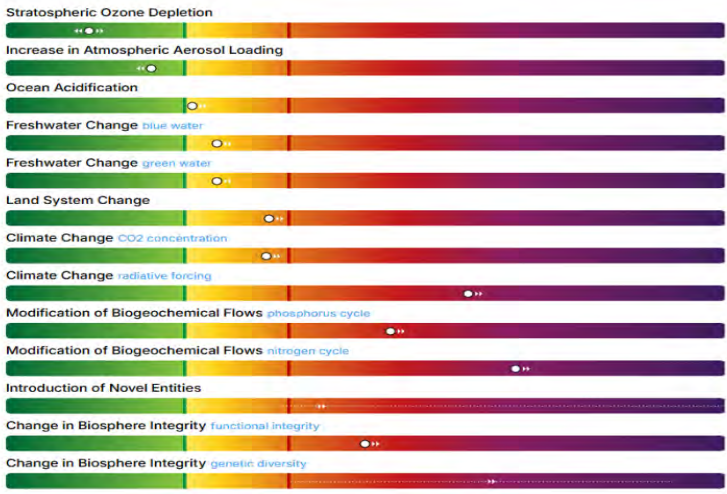


Figure 2. The Nine Planetary Boundaries and Their Current Status.
Source: https://www.stockholmresilience.org/research/planetary-boundaries.html

Digital Presence: Making the Invisible Visible

Geographic Information Systems (GIS), and particularly the ArcGIS StoryMaps format, represent a powerful instrument for the digital visibility of environmental actions - combining spatial data with text, images, and video to tell a compelling story about a specific place and issue[2]. The organization Mission Blue, led by Dr. Sylvia Earle, is one of the most illustrative examples of a blue enterprise using ArcGIS StoryMaps as a primary communication tool: through interactive maps of "Hope Spots", it visualizes endangered marine habitats around the world and mobilizes public support for their protection[10]. A similar approach is applied by the Living Oceans Foundation, whose StoryMaps from the Global Reef Expedition provide access to scientific data on coral reefs for policymakers, local

communities, and conservation organizations in an accessible and visually engaging format[8].

A particular notable example is the animated map produced by NASA's Scientific Visualization Studio, based on the ECCO model, which visualizes the movement of ocean currents at various depths in real scale rendering[9]. At the same time, the map illustrates the so-called "global conveyor belt" – a system of surface and deep-water currents that regulate the climate and distribute nutrients throughout the oceans over a millennial cycle. The scientific significance of visualization is twofold: on the one hand, it serves as a baseline for understanding the current state of ocean systems, and on the other, it functions as a tool for communicating the risks of climate change to these currents to a broad audience.

These examples demonstrate a key principle: digital visibility does not merely inform us, but it acts as a transformative link between scientific knowledge and public engagement, serving as a call to action and fulfilling precisely that multiplying function which blue marketing can provide for blue enterprises.

Case study: When design becomes ecological argument

The "No Blue, No Green" campaign, created by Droga5 São Paulo in collaboration with Black Madre Studio for the SOS Oceano coalition[16], stands as one of the most analytically compelling examples of blue marketing applied to marine conservation. The coalition unites seven Brazilian civil society organizations – Sea Shepherd Brazil, Instituto Baleia Jubarte, and Divers for Sharks, with the goal of expanding the country's marine protected areas and aligning national policy with UN SDG 14 and the Kunming-Montreal Global Biodiversity Framework.

The campaign unfolded in two phases. Phase one, launched at Rio Ocean Week in October 2025, deployed a single, high-impact visual gesture: the blue and green were removed from the Brazilian flag, leaving only the yellow diamond and white band as a silent manifesto that one ecosystem cannot exist without the other. Phase two, released in April 2026, shifted from subtraction to craft: six original screen-printed artworks, each pairing a marine species with its terrestrial counterpart within the yellow diamond of the flag, produced using natural mineral-based pigments developed specifically for the project.

The creative logic is rooted in color theory: blue and yellow produce green; remove the blue, and the green disappears. This makes the campaign's central ecological claim – that terrestrial life depends on a functioning ocean, not rhetorical, but visually and scientifically demonstrable.

The ocean absorbs approximately 30% of human-generated CO_2 and produces between 50% and 80% of atmospheric oxygen; without it, the conditions for forests, agriculture, and human settlement begin to degrade. The campaign condenses this systemic interdependence into an image that requires no scientific literacy to decode.

Viewed through the lens of this paper's theoretical framework, "No Blue, No Green" exemplifies the triadic relationship between planetary boundaries, blue marketing, and digital visibility. It does not merely inform – it reframes a national symbol as an ecological argument, achieves presence across physical and digital channels simultaneously (billboards, press, exhibition, social media, design publications), and does so on behalf of a coalition structure that multiplies reach without fragmenting the message. This is precisely the multiplying mechanism that effective blue marketing communication can activate – and the model against which the survey results of this study must be read

Survey study: from questions to action

The survey included 89 respondents in total – 80 Bulgarian and 9 international participants from France, Croatia, Portugal, Spain, and Italy. Among the Bulgarian respondents, 74% were female and 25% male, and the dominant age group was 36–50 years (60%), followed by 26–35 years (26.3%). The international group was similarly female-majority (78%), with most participants aged 26–35 years.

Awareness: Between Ignorance and Potential

The first measured indicator is awareness of the concept of the "blue economy" itself. The results reveal a significant gap in basic knowledge: only 30% of Bulgarian respondents declare that they are well acquainted with the concept, while 30% hear of it for the first time, and the remaining 40% have heard of it but are unsure of its meaning. The international group demonstrates considerably higher awareness – 56% identify themselves as well acquainted with the concept, which likely reflects the broader academic and political presence of the topic in the maritime economies of Western Europe.

Even more concerning is the indicator regarding concrete environmental actions taken by blue enterprises. Only 15% of Bulgarian respondents declare awareness of specific examples of such actions in the marine tourism, fisheries, or aquaculture sectors. More than half – 52% - have heard only general information, without specifics, and 34% are entirely uninformed. Among the international participants, the picture is slightly better: 33% are aware of specific examples, 44% have heard general information,

and 22% are not informed. These figures clearly show that even among people with an interest in the topic, the concrete actions of blue enterprises remain largely invisible.

The survey results gain particular significance considering current data on the state of water resources in Bulgaria. The report "Water Crises in Bulgaria"[12], prepared by a former Minister of the Environment and Water, presents a comprehensive picture of the deteriorating ecological condition of the country's water systems: temperatures have risen by 0.8°C relative to the 1961–1990 reference period, 2024 has been recorded as a record-breaking year, and river runoff for 2019 and 2020 was 36% and 45% below the norm respectively. Approximately 49% of surface water bodies fail to meet ecological standards. While the crisis is documented and measurable, public awareness of the actions taken by blue enterprises in response to it remains critically low.

Digital Communication: Insufficient but Desired

Regarding the digital communication of environmental actions, the assessments are unequivocal. 58% of Bulgarians consider that blue enterprises communicate their efforts insufficiently through digital channels, while only 5% rate it as sufficient. The international participants confirm the trend - 44% describe it as insufficient and 44% as partial. Neither group delivers a convincingly positive assessment of the current level of communication.

An analysis of preferred information channels reveals another important dimension. Social media plays the leading role (42% of responses for BG), followed by online media (36%), company websites (4%), while interactive maps and GIS platforms reach only 5%. This means that modern geospatial tools – such as the "Seeing the Unseen" platform[18] which visualizes the climate actions of Bulgarian municipalities – remain significantly underutilized as a communication channel to the wider public, despite their proven potential for making the "invisible visible".

A fundamental paradox of modern digital communication is that while we speak of "cloud services" and "data in the cloud", over 99% of intercontinental internet traffic physically travels through optical cables laid on ocean floor[1]. Every campaign for marine sustainability, every GIS visualization of an endangered reef, every call to action literally travels through the very ocean we are striving to protect. The digital economy is not an abstraction separate from nature - it is embedded within it, which makes the protection of ocean ecosystems a matter not only of ecology, but of critical infrastructure.

Motivation and Readiness for Action

Despite low levels of awareness, attitudes towards action are surprisingly strongly positive and reveal an enormous, untapped potential. When asked whether publicly available information about a company's environmental actions would influence their consumer choices, 93% of Bulgarian respondents answered affirmatively - "yes, definitely". Among the international group, this share stands at 75%. These figures unequivocally confirm that consumers are prepared to factor in the environmental behavior of enterprises in their decisions, provided they have access to clear and accessible information.

The leading motivation for supporting a blue enterprise among Bulgarians is the reduction of marine pollution (61%), followed by participation in the protection of marine protected areas (20%) and the application of sustainable production practices (10%). The international group reverses the priorities – placing participation in marine protected areas first (56%), with pollution reduction second (22%). This difference may reflect a more developed familiarity with the concept of marine protected areas in a Western European context, where conservation policies are more visible and publicly communicated.

The readiness for personal participation in initiatives for the protection of aquatic ecosystems, if well communicated, is particularly telling: 39% of Bulgarians would participate actively, and 59% conditionally. Among the international group, active readiness reaches 56%. Only 3% of Bulgarians and 11% of international participants rule out such engagement. The data speak unequivocally: the public will to participate in the protection of aquatic ecosystems exists – what is missing is solely the effective digital visibility to activate it and channel it towards concrete action.

Discussion

The survey data reveal a clear communication gap: most respondents cannot name specific environmental actions by blue enterprises, yet 93% state that such information would directly influence their consumer choices. This is not a crisis of action, but it is a crisis of visibility. The "No Blue, No Green" campaign by Droga5 São Paulo for SOS Oceano, alongside tools such as Mission Blue's Hope Spots StoryMaps, shows that when environmental data is translated into accessible visual narratives, it reaches audiences across digital and physical channels simultaneously. The present study is limited by sample size, particularly in the international group. A

follow-up study with a larger international sample is planned, and its findings will be presented in a subsequent paper.

Conclusion

The study confirms the initial thesis: the effect of the environmental actions of blue enterprises remains linear and contained without effective marketing communication, but when made publicly visible, it can become a multiplying mechanism for collective ecological change. The survey data show that awareness is low, yet willingness to act is high, which means the barrier is not motivation but access to clear information. By integrating the planetary boundaries framework, blue marketing principles and digital visibility tools such as GIS-based storytelling, enterprises can transform individual initiatives into scalable behavioral models. The results suggest three priorities: investing in transparent, data-rich narratives of environmental action tailoring these narratives to the channels where audiences are already attentive; and framing blue initiatives explicitly as contributions to restoring breached planetary boundaries. Future research could expand the empirical base across regions and sectors, and test specific communication formats experimentally to quantify their impact on behavior change.

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References:

1. Atlas (2026) 'Global Submarine Cables' [online]. Internet Infrastructure Map. Available at: https://atlas.co/maps/global-submarine-cables/ (accessed: 2026-06-02).
2. Esri (2020) 'A Little Hope Goes a Long Way: Mission Blue Uses ArcGIS StoryMaps to Bring Hope Spots to Life' [online]. Redlands, CA: Esri. Available at: https://tinyurl.com/384rs9rd (accessed: 2026-06-02).
3. European Commission (2021) Communication on a New Approach for a Sustainable Blue Economy in the EU: Transforming the EU's Blue Economy for a Sustainable Future. COM(2021) 240 final. Brussels: European Commission, 17 May. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:240:FIN (accessed: 2026-06-02).
4. European Commission; Joint Research Centre (2025) The EU Blue Economy Report 2025. Luxembourg: Publications Office of the European Union. Available at: https://bit.ly/4aQmGNh (accessed: 2026-06-02).

5. Findlay, H. S., Feely, R. A., Jiang, L.-Q., Pelletier, G. and Bednaršek, N. (2025) 'Ocean acidification: another planetary boundary crossed', Global Change Biology, 31, e70238. Available at: https://onlinelibrary.wiley.com/doi/10.1111/gcb.70238.
6. Institute of Sustainability Studies (2025) 'The role of communication in driving sustainable development' [online]. Institute of Sustainability Studies. Available at: https://bit.ly/3SyRTyl (accessed: 2026-06-02).
7. Institute of Sustainability Studies (2025) 'Mastering sustainable marketing communication: tips & strategies' [online]. Institute of Sustainability Studies. Available at: http://bit.ly/4ePXGZ2 (accessed: 2026-06-02).
8. Khaled bin Sultan Living Oceans Foundation (2024) 'StoryMaps: A New Way to Explore our Findings from the Global Reef Expedition' [online]. Living Oceans Foundation. Available at: https://www.livingoceansfoundation.org/storymaps-a-new-way-to-explore-our-findings-from-the-global-reef-expedition (accessed: 2026-06-02).
9. Maps.com (2025) 'Mapping the Motion of the Oceans at Different Depths' [online]. Maps.com. Available at: https://www.maps.com/animated-ocean-currents-map-shows-currents-at-various-depths/ (accessed: 2026-06-02).
10. Mission Blue and Esri (2020) 'Mission Blue Hope Spots' [online]. Mission Blue. Available at: https://mission-blue.org/hope-spots/ (accessed: 2026-06-02).
11. Planetary Boundaries Science Lab, Potsdam Institute for Climate Impact Research (PIK) (2025) Planetary Health Check 2025: A Scientific Assessment of the State of the Planet [online]. Potsdam: PIK. Available at: https://www.planetaryhealthcheck.org (accessed: 2026-06-02).
12. Popov, Y. and Dimitrov, P. (2026) Water Crises in Bulgaria: Analysis and Solutions. Sofia: Ministry of Environment and Water, March 2026. Available at: https://bit.ly/4xBEIwG (accessed: 2026-06-02).
13. Rockström, J., Steffen, W., Noone, K. et al. (2009) 'Planetary boundaries: exploring the safe operating space for humanity', Ecology and Society, 14(2), art. 32. Available at: https://www.ecologyandsociety.org/vol14/iss2/art32 (accessed: 2026-06-02).
14. Richardson, K., Steffen, W., Lucht, W. et al. (2023) 'Earth beyond six of nine planetary boundaries', Science Advances, 9(37), eadh2458. Available at: https://www.science.org/doi/10.1126/sciadv.adh2458 (accessed: 2026-06-03).
15. SIS International Research (2024) 'Marketing "Blue", not Green Products' [online]. New York: SIS International Research. Available at: https://tinyurl.com/y95rzhzu

16. Stash Media (2026) 'Black Madre & Droga5: "No Blue, No Green" for SOS Oceano' [online]. Stash Media, 5 April. Available at: https://www.stashmedia.tv/black-madre-droga5-no-blue-no-green-for-sos-oceano/ (accessed: 2026-06-03).
17. Steffen, W., Richardson, K., Rockström, J. et al. (2015) 'Planetary boundaries: guiding human development on a changing planet', Science, 347(6223), 1259855. Available at: https://www.science.org/doi/10.1126/science.1259855 (accessed: 2026-06-03).
18. Spasova, V. and Dyulgerski, D. (2025) Seeing the Unseen: GIS Platform for Climate Action and the Carbon Footprint of Bulgarian Municipalities (ArcGIS StoryMap) [online]. Available at: https://bit.ly/3S6VMKS (accessed: 2026-06-02).
19. Suryawijaya, T. W. E., Utomo, M. T. R. S., Fader, P. S., Wibowo, M. E. S., Fitroh, F. I. and Priyono, A. (2024) 'Blue-marketing strategy: the opportunities and challenges of big data integration in coastal MSMEs', International Journal of Accounting, Management and Economics Research, 2(1), pp. 61–80. Available at: https://tinyurl.com/3rpss583.
20. United Nations (2024) The Sustainable Development Goals Report 2024. New York: United Nations. Available at: https://unstats.un.org/sdgs/report/2024/The-Sustainable-Development-Goals-Report-2024.pdf (accessed: 2026-06-02).
21. United Nations and World Bank Group (2017) The Potential of the Blue Economy: Increasing Long-term Benefits of the Sustainable Use of Marine Resources for Small Island Developing States and Coastal Least Developed Countries. Washington, DC: World Bank. Available at: https://tinyurl.com/yc36vnew (accessed: 2026-06-02).

OFFSHORE WIND ENERGY IN POLAND: THE FUTURE OF SUSTAINABLE POWER

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Abstract: *This paper examines the development of offshore wind energy in Poland within the European Union's energy transition, with a focus on the Baltic Sea. It analyzes regulatory frameworks, investment mechanisms, and technological advancements, as well as key economic and infrastructural challenges. The study evaluates the role of offshore wind in strengthening energy security, diversifying the energy mix, and reducing emissions.*

Keywords: *offshore wind energy, energy transition, decarbonization, Baltic Sea, energy security, renewable energy policy, grid integration, local content, sustainable development, Poland*

1. Introduction

The transformation of the Polish energy sector represents one of the most significant economic and structural changes in the country since the political transition of 1989. Historically, Poland has relied heavily on coal as the primary source of electricity generation, which has shaped both its industrial development and energy infrastructure. However, increasing environmental concerns, European Union climate policies, and geopolitical instability have accelerated the need for diversification of energy sources.

In this context, offshore wind energy has emerged as a key solution. The Baltic Sea offers highly favorable conditions for the development of offshore wind farms, including shallow waters, relatively stable wind patterns, and proximity to industrial and urban centers. As of 2026, Poland has entered the implementation phase of offshore wind projects, with approximately 4.5 GW of capacity under construction and further expansion planned in the coming decades. (1)

This paper aims to analyze the role of offshore wind energy in Poland's energy transition, focusing on regulatory frameworks, technological advancements, economic impacts, and infrastructure challenges.

Key Metric	Status / Projection (2025/2026)	2030 Target	2040 Target
Installed OffshoreCapacity	0 GW (4.5 GW in construction)	5.9 - 6.0 GW	2040 Target
Share of RES in Electricity	~31% (low-carbonsources)	51.8%	79.8%
Annual Electricity-Demand	154 TWh (2024)	~200 TWh	210-270 TWh
Total NPS InstalledCapacity	~72 GW	>90 GW	~180 GW
Carbon Intensity (CO_2e/kWh)	666g (2024)	Target Reduc-tion~50%	Near-Zero

Source: KPMG, The Draft Update of the National Energy and Climate Plan 2030 Adopted by the Ministry of Climate and Environment.

2. Regulatory Framework and Policy Context

The development of offshore wind energy in Poland is strongly supported by national

and European policy frameworks. The key strategic document is the Energy Policy of Poland until 2040 (PEP2040), which defines the country's long-term approach to energy transformation. (2) The policy emphasizes three main objectives: ensuring energy security, improving environmental sustainability, and enhancing economic competitiveness. (3)

In response to evolving geopolitical conditions and the European Green Deal, Poland has updated its National Energy and Climate Plan (KPEiK). The plan introduces two scenarios: the "With Existing Measures" (WEM) scenario and the more ambitious "With Additional Measures" (WAM) scenario. (4) The differences between the WEM and WAM scenarios are summarized in Table 2.

Table 2. Differences between the WEM and WAM scenarios

	2030 RES Share (Electricity)	2040 RES Share (Electricity)	2030 GHG Reduction	2040 GHG Reduction
WEM (Business as Usual)	51.6%	~60%	43%	61%
WAM (Active Transition)	51.8%	79.8%	53.9%	75%

Sources: KPMG, *The Draft Update of the National Energy and Climate Plan 2030 Adopted by the Ministry of Climate and Environment;* Balticwind.eu, M. Moskał, *Polish Ministry of Energy published draft National Energy and Climate Plan for 2030 and 2040 – key document for Polish energy sector and economy.*

The WAM scenario assumes accelerated decarbonization, targeting a reduction of greenhouse gas emissions by 53.9% by 2030 compared to 1990 levels. (4)

Offshore wind energy is considered a critical component of achieving these targets. As coal-fired power plants are gradually phased out, offshore wind will help fill the resulting energy gap. The expected increase in electricity demand, driven by electrification of transport and industry, further reinforces the importance of renewable energy sources. The Offshore Wind Act, adopted in 2021, established the legal foundation for the sector. It introduced a support system based on Contracts for Difference (CfD), which provide financial stability for investors. Amendments introduced in 2025 improved the regulatory environment by streamlining administrative procedures, enhancing transparency, and enabling more efficient allocation of maritime areas for renewable energy projects. (3)

3. Geographic and Technical Conditions

The Baltic Sea provides unique advantages for offshore wind energy development. One of the most significant factors is its relatively shallow depth, averaging around 55 meters. (5) This allows for the use of fixed-bottom foundations, such as monopiles, which are more cost-effective and technologically mature compared to floating structures.

In addition to favorable seabed conditions, the Baltic Sea is characterized by stable wind patterns. Although wind speeds are slightly lower than in the North Sea, their consistency contributes to predictable energy production. However, certain meteorological phenomena, such as low-level jets, must be taken into account when designing turbines and forecasting energy output.

Technological advancements have significantly improved the efficiency of offshore wind farms. Modern turbines used in Polish projects have capacities of 14-15 MW, with rotor diameters exceeding 220 meters and total heights reaching approximately 250 meters. (1) The key technical parameters of offshore wind projects are presented in Table 3.

These large-scale turbines enable higher energy yields and reduce the number of installations required to achieve target capacity levels.

At the same time, the size and weight of these components pose logistical challenges, requiring specialized vessels, reinforced port infrastructure, and advanced installation techniques.

Table 3. Key technical parameters of offshore wind projects

Project Phase	Capacity (GW)	Support Mechanism	Key Developers	Estimated Commissioning
Phase I (Advanced)	4.5 GW	Individual CfD	Orlen, PGE, Ørsted, Equinor, Polenergia	2026 - 2028
Phase I (Remaining)	1.4 GW	Individual CfD	PGE, Ørsted	2029 - 2030
Phase II (Auction)	3.4 GW	Competi-tive CfD	PGE, Orlen	2032+

Sources: Acteon, Poland's offshore wind potential: Navigating policies, local sourcing and energy independence.

4. Project Development and Market Structure

The development of offshore wind energy in Poland is structured in two main phases.

Phase I consists of projects that received support through administrative decisions, while Phase II is based on competitive auctions. (6)

Phase I includes several major projects currently under construction. Among them, Baltic Power, Baltica 2, Bałtyk 2 and 3, and BC-Wind are the most advanced. These projects represent the first large-scale implementation of offshore wind technology in Poland and are expected to become operational between 2026 and 2028. (8)

Phase II marks the transition toward a more market-oriented approach. In 2025, the first competitive auctions were conducted, resulting in the allocation of contracts for over 3.4 GW of capacity. (1) This phase introduces greater competition among developers and is expected to drive cost reductions and technological innovation.

Project Phase	Capacity (GW)	Support Mechanism	Key Developers	Estimated Commissioning
Phase I (Advanced)	4.5 GW	Indiviual CfD	Orlen, PGE, Ørsted, Equinor, Polenergia	2026 - 2028
Phase I (Remaining)	1.4 GW	Individual CfD	PGE, Ørsted	2029 - 2030
Phase II (Auction)	3.4 GW	Competitive CfD	PGE, Orlen	2032+

Sources: Enerdata, Poland approves draft revised NECP with 2030–2040 outlook.

The development of these projects involves cooperation between domestic and international companies. Partnerships with experienced foreign

developers enable the transfer of knowledge and access to global supply chains, which are essential for the successful implementation of complex offshore projects.

5. Economic Aspects

The offshore wind sector is characterized by high capital intensity and long investment cycles. Initial costs include turbine manufacturing, installation, grid connection, and infrastructure development. However, once operational, offshore wind farms have relatively low operating costs and provide stable, long-term energy production.

In Poland, the offshore wind sector is supported by significant financial investments, estimated at approximately €65 billion. The Contracts for Difference mechanism plays a crucial role in ensuring financial viability by guaranteeing a stable revenue stream for project developers.

Operational costs, particularly maintenance and servicing, represent a significant portion of total expenses, typically accounting for 20-25% of the levelized cost of energy. (1) These activities require specialized personnel and equipment, contributing to the development of local industries and job creation.

From a macroeconomic perspective, offshore wind energy is expected to reduce electricity prices in the long term. By increasing the share of low-cost renewable energy sources, Poland can reduce its dependence on fossil fuels and mitigate the impact of carbon pricing mechanisms within the European Union.

6. Infrastructure Challenges

Despite its potential, the development of offshore wind energy in Poland faces significant infrastructure challenges. One of the most critical issues is the limited capacity of the national electricity grid. The existing transmission system was designed to distribute energy from coal-fired power plants located in the southern part of the country, whereas offshore wind farms are concentrated in the north.

To address this mismatch, Poland is implementing a large-scale grid modernization program. The Grid Act, adopted in 2026, introduced measures aimed at improving the efficiency of connection processes and increasing system capacity. These measures include the introduction of application fees, mandatory financial guarantees, and digitalization of administrative procedures.

In addition to grid infrastructure, port facilities must be upgraded to support offshore wind projects. The installation and maintenance of large

turbines require specialized ports equipped with heavy-lift cranes, storage areas, and assembly facilities. Investments in ports such as Gdańsk, Szczecin, and Świnoujście are essential for the development of the sector. (10)

7. Local Content and Industrial Development

A key objective of Poland's offshore wind strategy is to maximize domestic participation in the sector. The concept of "local content" refers to the share of goods and services provided by domestic companies in the implementation of projects.

The Polish government has set a target of achieving at least 45% local content by 2030. (5) To support this goal, a formal framework has been introduced, defining criteria for domestic entities based on factors such as revenue generation, tax residency, employment, and ownership structure.

The development of local content is expected to stimulate economic growth, create jobs, and enhance the competitiveness of Polish companies.

Domestic Player	Area of Expertise	Role in 2026 Projects
TELE-FONIKA Kable	Land and sea cables	Manufacturing and installation services.
Energoaparatura	Electrical power and automation	MV/HV installations, substations, and I&C.
CRIST Offshore	Steel structures and OSS	EPC-level supply of offshore substations.
Aarsleff BIZ	Precast concreto elements	Manufacturing concrete work platforms for foundations.
Orlen Neptun	Marine environment surveys	Environmental impact assessments for Baltic West.

Sources: Polish Investment and Trade Agency, Powering Europe Together - Poland's Role in the Offshore Wind Future.

It also facilitates the transfer of knowledge and technology from international partners, enabling domestic firms to participate in global supply chains. However, achieving these targets requires significant investment in education, training, and industrial capacity. The current level of domestic participation remains relatively low, highlighting the need for continued policy support and strategic partnerships.

8. Security and Geopolitical Considerations

The expansion of offshore wind energy in the Baltic Sea has important geopolitical implications. The region is characterized by strategic sensitivity, particularly due to its proximity to Russia and the presence of critical infrastructure such as pipelines and communication cables.

Offshore wind farms, including turbines, substations, and subsea cables, are considered critical infrastructure and may be vulnerable to various threats, including cyberattacks, sabotage, and hybrid warfare tactics. Ensuring their security is therefore essential for maintaining energy stability and national security.

Poland is actively strengthening its defense capabilities and cooperating with regional partners to enhance the protection of offshore installations. This includes the integration of security considerations into the planning and design of wind farms, as well as the development of monitoring and response systems.

9. Social Impact

The development of offshore wind energy has significant social implications, particularly in coastal regions. The sector is expected to create a substantial number of jobs in construction, operation, maintenance, and related industries.

In addition to direct employment, offshore wind projects contribute to regional development by stimulating investment in infrastructure, education, and local businesses. Training programs and educational initiatives are being implemented to prepare the workforce for the demands of the sector.

Furthermore, the transition to renewable energy is expected to reduce energy poverty by lowering electricity costs and improving access to affordable energy. This is particularly important for maintaining public support for the energy transition.

10. Conclusion

Offshore wind energy represents a cornerstone of Poland's transition toward a sustainable and secure energy system. The sector has progressed from planning to implementation, with significant capacity under construction and ambitious targets for future expansion.

The analysis presented in this paper highlights the multifaceted nature of offshore wind development, encompassing regulatory, technological, economic, and social dimensions. While challenges remain, particularly in terms of infrastructure and investment costs, the overall outlook for the sector is highly positive.

Offshore wind energy offers numerous benefits, including reduced greenhouse gas emissions, enhanced energy independence, economic growth, and improved living standards. As Poland continues to develop its

offshore wind capacity, the Baltic Sea will play a central role in shaping the country's energy future.

References:

1. Bálint Szalai (25.02.2026) Poland offshore wind. Retrieved May 20, 2026, from CE Energy News
2. Government of Poland – Energy Policy of Poland until 2040. (n.d.). Energy policy of Poland until 2040.
3. Government of Poland – Ministry of Climate and Environment. (16.10.2025). The Senate unanimously passed the act on offshore wind Energy
4. KPMG Poland. (n.d.). Legal alert: The draft update of the National Energy and Climate Plan 2030 adopted by the Ministry of Climate and Environment.
5. Polish Wind Energy Association (PSEW). (n.d.). Believe in the Baltic Sea and its tremendous offshore wind potential
6. Baltic Power – About the Project. (n.d.). About the project.
7. Ørsted. (11.052026). Ørsted and PGE kick off offshore installation of Baltic Power.
8. Adrijana Buljan (18.02.2026). Offshore construction starts on Polish Baltyk 2 & 3 wind farms.
9. Wojciech Świercz, Grzegorz Kaczor, Mikolaj Matuszko, Kamil Moskwik, Piotr Ćwiek. (12.2025). Poland energy outlook 2026 and beyond. Polish Wind Energy Association (PSEW). (n.d.) Offshore wind potential in Poland.=

IMPLEMENTING THE CIRCULAR ECONOMY IN MARINE SECTORS

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Abstract: *The maritime sector is a strategic pillar of the European Union's economy, yet it faces escalating environmental pressures including pollution, biodiversity loss, and climate-induced degradation. Circular Economy (CE) principles offer a systemic alternative to the linear "take–make–dispose" model, aiming to enhance resource efficiency, reduce waste, and regenerate marine ecosystems. This article synthesizes theoretical frameworks, implementation barriers, and practical case studies of CE in marine sectors, drawing on EU policy documents, international conventions, and contemporary initiatives such as Healthy Seas, Fishing for Litter, the Port of Rotterdam industrial symbiosis model, and the Blue-CCRI project. Additionally, it integrates insights from the educational initiative Trashformers, demonstrating how youth-driven environmental engagement complements systemic CE transitions. The analysis reveals that while CE adoption is hindered by legal fragmentation, economic constraints, and technological gaps, coordinated policy action, innovation, and cross-sectoral collaboration can accelerate the transformation toward a sustainable and resilient Blue Economy.*

Keywords: *Circular Economy, Blue Economy, Marine Sectors, Blue-CCRI, Ship Recycling, Industrial Symbiosis, Marine Waste, Regulatory Barriers, Healthy Seas*

Introduction: Marine Sectors in the European Union

The maritime sector—including shipping, fisheries, aquaculture, offshore energy, coastal tourism, and port logistics—constitutes a strategic component of the EU economy, generating over €250 billion annually and supporting more than 5 million jobs. Its importance extends beyond economic metrics: maritime industries underpin food security, energy transition, and global trade flows.

However, the sector faces intensifying environmental pressures. According to UNEP, oceans are at the center of a triple planetary crisis: climate

change, biodiversity loss, and pollution. Marine ecosystems are increasingly degraded by plastic waste, chemical contaminants, overfishing, and climate-induced stressors such as acidification and warming. These pressures expose the limitations of the linear economic model, which relies on continuous extraction and disposal of resources.

In this context, the Circular Economy emerges as a strategic framework for transforming marine sectors. CE aims to decouple economic growth from resource consumption by promoting waste reduction, material circulation, and ecological regeneration. As the EU's Blue Economy strategy emphasizes, CE is essential for achieving long-term sustainability, competitiveness, and resilience in ocean-based industries.

Conceptualizing the Circular Economy in Marine Sectors

From linear to circular systems are contemporary cocepts. The Ellen MacArthur Foundation defines CE as a systemic shift from the linear "take–make–dispose" model toward an economy that eliminates waste, retains material value, and regenerates natural systems. In marine sectors, this transition involves designing vessels and port infrastructure for durability and reparability, recovering and recycling materials such as ship steel, fishing nets, and port waste, reducing environmental externalities across maritime value chains, and integrating renewable energy and low-carbon technologies.

The Core Principles of CE in marine sectors is grounded in three pillars:

- Waste elimination through design and operational changes.
- Value retention via reuse, repair, remanufacturing, and recycling.
- Regeneration of marine ecosystems and natural capital.

These principles align with the EU Green Deal, which identifies CE as a key driver of resource security and environmental protection.

Theoretical Frameworks Supporting CE in Marine Sectors

The ecological economics emphasizes biophysical limits and the need to align economic activity with ecological capacity. Marine ecosystems cannot indefinitely absorb waste or regenerate resources at the pace demanded by linear production systems.

The Polluter Pays Principle assigns responsibility for environmental harm to those who generate it. In marine sectors, it supports extended producer responsibility for fishing gear, stricter ship recycling obligations, and accountability for port waste management.

The Blue Economy, promoted by OECD and UNEP, integrates economic development with marine conservation. It highlights sustainable

fisheries and aquaculture, decarbonisation of maritime transport, circular port operations, and innovation in blue biotechnology.

The systems thinking analyzes interdependencies within maritime value chains. It is essential for mapping material flows, identifying circular opportunities, and designing industrial symbiosis networks. Together, these frameworks provide a coherent theoretical basis for CE implementation.

Circular Economy Models in Marine Sectors

The regenerative model focuses on restoring marine ecosystems through sustainable fisheries management, habitat protection, and reduction of destructive practices. The Material Circulation Model is related to the identification of material loops - central to CE. In marine sectors, this includes recycling ship steel, recovering fishing nets, processing port waste, and reusing dredged materials. Healthy Seas exemplifies this model by transforming discarded fishing nets into ECONYL® nylon.

The Service-Based Model and its approaches reduce resource consumption by promoting shared access to maritime infrastructure, leasing rather than owning equipment, and collaborative vessel maintenance systems. The Industrial symbiosis involves resource exchange between co-located industries. The Port of Rotterdam is a leading example, enabling CO_2 reuse, waste heat exchange, and shared logistics and energy systems.

Barriers to Implementing the Circular Economy in Marine Sectors

Despite its potential, CE adoption faces significant legal, economic, and technological obstacles.

Legal Barriers: Fragmented Governance and Regulatory Misalignment. Those legal barriers constitute one of the most significant obstacles to CE implementation. EMSA reports that ship recycling is governed by a complex combination of EU legislation and international conventions, resulting in regulatory fragmentation. Divergent national interpretations further complicate compliance, creating uncertainty for operators.

Restrictions on the transboundary movement of waste under the Basel Convention complicate recycling logistics, especially when specialised facilities are located abroad. The absence of unified CE standards across Member States limits innovation, discourages investment, and slows the development of circular maritime hubs.

The Economic Barriers: High Costs, Low Profitability, and Limited Incentives. OECD analyses show that circular technologies require

substantial capital investment, while the profitability of recycling marine materials—particularly composites—remains low. Many companies lack access to financial incentives or stable funding mechanisms.

The Blue-CCRI project highlights insufficient regional coordination and inadequate financial support as major obstacles to establishing circular hubs. As a result, firms often perceive CE as financially risky, despite its long-term benefits.

Technological Barriers: Infrastructure Deficits and Limited Innovation Capacity. Technological constraints further impede CE integration. Many ports lack advanced waste-recovery infrastructure, and digitalisation remains insufficient to enable effective monitoring of material flows. Blue-CCRI identifies the absence of reliable data on resource use as a critical barrier.

Recycling technologies for fishing nets, composites, and mixed maritime waste streams remain underdeveloped. EMSA reports that numerous ship dismantling facilities lack modern equipment required for safe and efficient material recovery.

Some sase studies are good enough in emonstrating the Feasibility of Circular Solutions. Despite these challenges, several initiatives demonstrate that CE implementation in marine sectors is both feasible and beneficial. One of them is the Healthy Seas, which collects abandoned fishing nets and transforms them into ECONYL® nylon, creating a circular value chain linking marine conservation with sustainable production.

Fishing for Litter engages fishers in removing marine debris during routine operations, reducing pollution and strengthening cooperation between the fishing sector and environmental organisations. The Port of Rotterdam exemplifies industrial symbiosis through the reuse of CO_2 and waste heat, demonstrating how ports can serve as hubs for circular innovation. The Blue-CCRI develops regional circular hubs connecting ports, enterprises, and research institutions, accelerating the transition toward circular maritime systems.

Conclusions

Considering the trend **Toward a Circular and Resilient Blue Economy**, we must understand that the Circular Economy is essential for the sustainable transformation of marine sectors. Although legal, economic, and technological barriers persist, they can be mitigated through harmonised regulations, targeted financial incentives, investment in infrastructure, and strengthened cooperation.

Existing initiatives such as Healthy Seas, Fishing for Litter, the Port of Rotterdam, and Blue-CCRI demonstrate that CE can enhance both environmental protection and economic competitiveness. Achieving a circular and resilient Blue Economy will require coordinated policy action, technological innovation, and sustained collaboration across sectors and governance levels.

References:

1. Blue Economy (European Commission) - https://maritime-forum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy_en
2. The butterfly diagram: visualising the circular economy, 12 February 2021 (Ellen MacArthur Foundation) - https://www.ellenmacarthurfoundation.org/circular-economy-diagram
3. Ocean, seas and coasts, 24 February 2026 (UNEP - UN Environment Programme) - https://www.unep.org/topics/ocean-seas-and-coasts
4. Technical reports, studies and plans, 2026 (European Maritime Safety Agency) - https://www.emsa.europa.eu/publications/reports.html
5. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) - https://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx
6. Preparing the Research & Innovation Core for Mission Ocean, Seas & Waters (CORDIS - EU research results) - https://cordis.europa.eu/project/id/101056957
7. Protecting the Seas, Transforming Marine Litter , 2026 (Healthy Seas) - https://www.healthyseas.org/
8. Fishing for Litter (KIMO) - https://www.kimointernational.org/fishing-for-litter/
9. Welcome to the port of Rotterdam (Port of Rotterdam) - https://www.portofrotterdam.com/en



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