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USED CAR MARKETING STRATEGY RECOMMENDATION: A STRUCTURAL EQUATION MODELING APPROACH

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Abstract. In recent years, China's used car market has experienced rapid growth. However, constrained by non-standardization, lack of trustworthiness, and dual competitive pressures from emerging e-commerce platforms and traditional dealers, optimizing corporate marketing strategies has become an urgent priority. This study takes three first-tier city used car enterprises—Beijing Guazi, Guangzhou Cheyou, and Shanghai Youxin, as research subjects, employing quantitative research methods to explore the influencing factors behind performance improvement in the used car industry. The results show that: (1) the marketing mix (4Ps) serves as the core driver of customer satisfaction, attractiveness, and corporate performance, directly determining the effectiveness of personalized marketing implementation; (2) while personalized marketing requires precise execution, external environmental factors exert limited influence; (3) enhancing corporate performance necessitates the synergy of both marketing and non-marketing factors. Based on these findings, it is recommended that enterprises center their efforts on the 4Ps to optimize product pricing, channel integration, and other aspects, deepen big data-driven precision personalized marketing, and establish a full-link mechanism of "acquiring customers through marketing—retaining customers with quality—locking in customers via service." This study provides empirical support for strategy optimization in used car enterprises and enriches both the theory and practice of marketing transformation in the industry.

Keywords: China; used cars; improve performance; marketing mix; personalization; quantitative research

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JEL Classifications: O11

1. Introduction

In 2024, China saw about 19 million used car sales, nearly a fivefold increase since 2010, reflecting strong market growth (China Automobile Dealers Association, 2025). The expansion of China's used car market size and growth in transaction volume also reflect rising consumer acceptance of second-hand goods and improved market circulation efficiency. In the current used car market environment, used car sales enterprises face intense competition from emerging e-commerce platforms and traditional dealers (Feng, Qin & Zhi, 2025). These challenges impede their performance improvement and call for optimized marketing strategies to address. The

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pattern where intensified market competition constrains enterprise performance growth is prevalent across transitional industries, and optimizing marketing strategies represents a core pathway for enterprises to break through competitive barriers and achieve differentiated development.

This study focuses on three leading used car enterprises in first-tier cities—Beijing Guazi, Guangzhou Cheyou, and Shanghai Youxin. Through cross-regional comparative analysis, it accurately captures the impact of market heterogeneity on corporate strategies, providing empirical support for the industry's differentiated development and helping enterprises optimize strategies and enhance performance.

At the theoretical level, this research fills the gap in studies on marketing strategies at the enterprise level in China's used car industry, enriching academic literature on corporate competitive strategies amid automotive industry transformation. At the practical level, the findings will offer actionable strategic references for enterprises, directly improving consumer purchasing experiences.

2. Review Literature and Hypotheses

Among the multi-dimensional research literatures focusing on the global and Chinese used car markets, the following key findings are as follows.

In China, policy measures (such as removal of relocation restrictions and tax cuts) and upgraded consumer concepts (emphasizing environmental protection and cost-effectiveness) serve as core drivers (Barwick, Cao & Li, 2021). China's transaction volume is expected to exceed 30 million units by 2025, with regional strategies diverging: First-tier cities are dominated by brand services (e.g., certified warranties, transparent vehicle conditions); second- and third-tier cities exhibit high price sensitivity, requiring channel penetration (Liu & Song, 2023; Zhang et al., 2025).

Digital marketing, social media, and integration have become trends (Nithisathian et al., 2020). Younger groups (aged 25–35) exhibit high online platform usage, yet enterprises often lack word-of-mouth incentives (Azadnia et al., 2022; Siregar, Suroso & Krisnatuti, 2024). Key decision factors are price, vehicle condition transparency, and after-sales guarantees. The trust-cost dilemma has emerged: vehicle condition transparency (via blockchain) and third-party inspections enhance trust, but cost control remains unresolved; dynamic pricing improves short-term efficiency, yet long-term brand premium quantification is difficult (Engelmann et al., 2022; Beck, Wuyts & Jap, 2023; Engelmann & Schwabe, 2024; Sun et al., 2025).

Traditional dealers compete against online platforms, where service and brand determine success (Feng, Qin & Zhi, 2025). Current used car sales companies (e.g., Beijing Guazi, Guangzhou Cheyou, Shanghai Youxin, etc.) face multiple challenges. Emerging e-commerce platforms have rapidly captured market share through strategies like low-price models, large-scale advertising, and big data-driven precision marketing (Steinberg, 2021). Traditional dealers have also intensified competition by leveraging the advantages of their offline after-sales networks, making market share capture increasingly difficult (Feng, Qin & Zhi, 2025).

Consumer demands are becoming increasingly diverse, and there is pressure from imports, as well as a preference for new cars (Ramani, 2025). Yet enterprises lag in demand response speed and personalized service adaptation. Coupled with issues such as insufficient transparency in vehicle condition, building trust remains a significant challenge. Internal operational shortcomings are equally prominent: Inefficient integration of digital marketing tools (social media, SEO) leads to low lead conversion rates; Business is overly concentrated on the transaction process, with follow-up services (e.g., after-sales maintenance) lagging behind (Feng, Qin & Zhi, 2025); Profit models rely heavily on purchase-resale spreads, causing profit margins to narrow continuously amid intensifying competition; High costs for brand building and technology R&D create an urgent need to control expenses and improve efficiency (Azadnia et al., 2022).

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Theoretical framework of the study is based on the following theories. Marketing Mix Theory (4Ps) framework can be used in the car market, validating its effectiveness in enhancing market competitiveness through dynamic pricing and optimization of the online-to-offline (O2O) distribution system.

Personalized Marketing Theory can be applied for car industry. Chen, Zhang and Wang (2025) provided empirical support for used car enterprises to design differentiated communication strategies and improve customer satisfaction by leveraging precision recommendation technology based on big data analysis.

Relationship Marketing Theory emphasizes role of relationship marketing guiding used car enterprises to build long-term customer relationships through loyalty programs and emotional connections. Customer Value Theory proposes a performance measurement framework encompassing four dimensions of customer value (functional, emotional, social, and cost), which helps used car enterprises optimize perceived customer value (Azadnia et al., 2022). Service Marketing Theory suggests the service marketing 7Ps model, which could be applied to analyze companies' experience in used car sales, verifying its role in enhancing the full-process pre-sale, in-sale, and post-sale services. The theoretical framework diagram is shown in Figure 1.

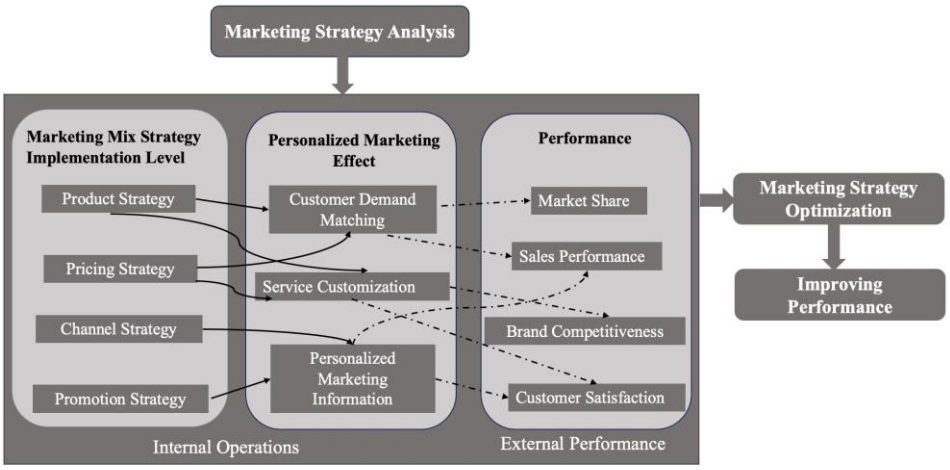


Figure 1. Theoretical framework for research on used car company marketing strategy
Source: the authors

Statistical analysis was used to validate research hypotheses. The following preliminary hypotheses are proposed:

H1. Respondents are satisfied with the current product, pricing, distribution, and promotion strategies of Chinese used car companies.
H2. The marketing mix strategies (product, pricing, distribution, promotion) of Chinese used car companies effectively meet customer needs to a certain extent.
H3. Chinese used car companies demonstrate a certain degree of effectiveness in implementing personalized marketing strategies (content marketing, social media interaction, promotions, customer service).
H4. The implementation level of marketing mix strategies has a significant positive impact on the effectiveness of personalized marketing strategies in Chinese used car companies.
H5. Chinese used car companies face a series of major challenges and obstacles (including product development bottlenecks, pricing strategy dilemmas, distribution channel barriers, and promotion method limitations) when implementing their marketing mix strategies.
H6. Based on the research findings, propose marketing strategy recommendation methods to improve corporate performance.

Focusing on the core topic of "optimizing marketing strategies and enhancing performance for Chinese used car enterprises," this study systematically constructs a logical analytical framework of "marketing strategy implementation → customer indicators (satisfaction, attractiveness) → business performance," grounded in the

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Resource-Based View (RBV), Relationship Marketing Theory, and Dynamic Capabilities Theory. The specific variable design is as follows:

Independent variables: Marketing mix strategy, effectiveness of personalized marketing, personalized marketing strategy, market competition pressure, and changes in consumer demand.

Dependent variables: Customer satisfaction, customer attractiveness, marketing mix strategy, effectiveness of personalized marketing strategy, personalized marketing strategy, and business performance.

Moderating variables: The effectiveness of personalized marketing strategies in attracting customers and internal resources.

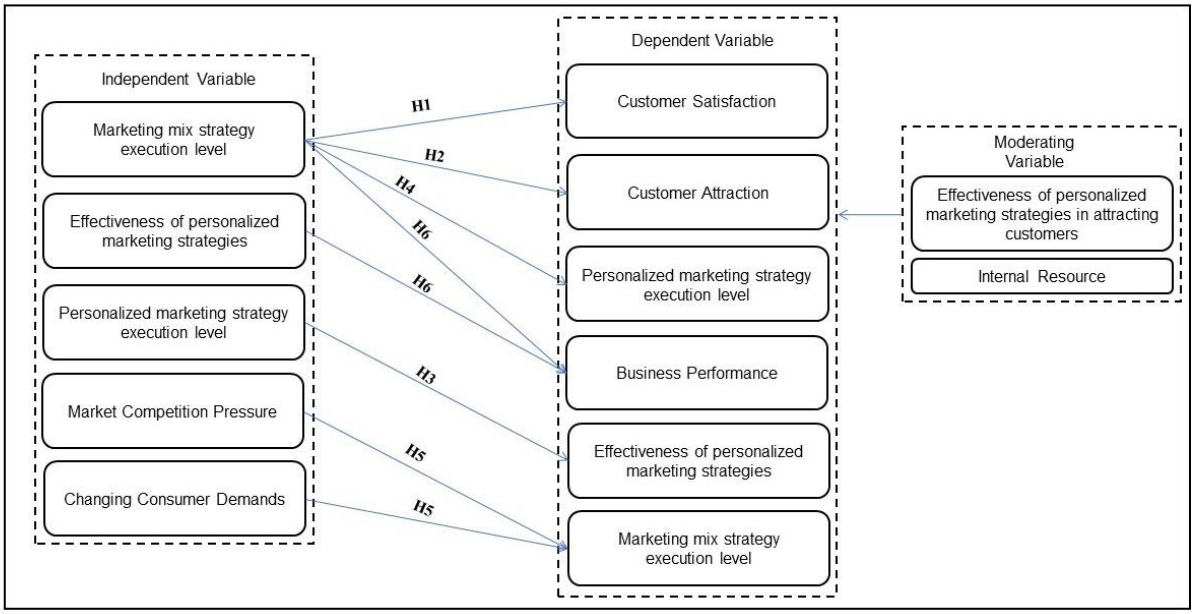


Figure 2. Conceptual Framework of Used Car Company Marketing Strategy Recommendation Research
Source: the authors

The relationships among these variables are illustrated in Figure 2, ultimately demonstrating the logical path through which marketing strategy implementation influences business performance via customer indicators.

3. Research Methods

3.1. Research Design

The study focuses on optimizing marketing strategies for used car businesses, adopting quantitative analysis methods to collect data through questionnaire surveys. It aims to identify key factors influencing strategies and test hypotheses, providing data-driven recommendations for enterprises. The sample covers three companies—Beijing Guazi, Guangzhou Cheyou, and Shanghai Youxin—with a total of 360 respondents (including managers, employees, and customers). Random sampling was conducted proportionally by organizational hierarchy to ensure representativeness. Descriptive statistics, correlation analysis, and other methods were employed to evaluate the impact of factors and test the hypotheses. Adhering to ethical standards, the study ensures participant anonymity and data security, with operations regulated through informed consent procedures. It offers multi-dimensional insights into the current status of used car marketing strategies and pathways for optimization.

3.2. Instrumentation

This study uses questionnaires as the primary tool, aiming to analyze the recommended paths of used car marketing strategies and their impact on performance. The questionnaire is designed based on the research

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objectives, covering dimensions such as product, pricing, channel, promotion, personalized marketing, and customer value. The data is comprehensive, encompassing key factors for marketing strategies.

The questionnaire consists of two parts, and the questions are multiple-choice questions.

1. Part I: Basic information of respondents
Mainly collect the basic information of the respondents, including job category (senior, middle-level, front-line employees, users), age, gender, education and years of work experience.

2. Part II: Evaluation of existing marketing strategies (50 questions), see Table 1.

Table 1. Variables, items, survey questions and source reference

Variables	Items	Survey Questions	Source/Reference
Effectiveness of personalized marketing strategies in attracting customers（Items 1）	EPMS1	Personalized marketing messages make me more likely to consider buying a used car.	Chen, Zhang & Wang, 2025
	EPMS2	I believe that personalised promotions align with my specific needs and preferences.	
	EPMS3	Personalized recommendations increase my trust in the company.	
	EPMS4	I am more engaged with marketing messages that are tailored to me.	
	EPMS5	Personalized marketing encourages me to revisit the seller/platform.	
Internal Resource（Items 2）	IR2	The company has sufficient human resources with marketing expertise.	He et al., 2024
	IR3	Technological resources are effectively used to implement strategies.	
	IR4	Organizational structure supports the execution of marketing plans.	
	IR5	Internal knowledge and capabilities contribute to successful marketing.	
	IR2	The company has sufficient human resources with marketing expertise.	
Customer Satisfaction（Items 3）	CS1	I am satisfied with the overall purchasing experience.	Azadnia et al., 2022
	CS2	The company provides reliable and trustworthy services.	
	CS3	My expectations of the product/service are consistently met.	
	CS4	I would recommend this company to others.	
	CS5	I intend to repurchase from this company in the future.	
Customer Attraction（Items 4）	CA1	The company's marketing efforts attract my attention effectively.	Lee, Kim & Kim, 2021
	CA2	I am attracted to exploring the company's offerings after seeing its marketing.	
	CA3	Marketing campaigns increase my willingness to interact with the company.	
	CA4	Marketing communication makes me prefer this company over others.	
	CA5	I am more likely to follow up after receiving marketing messages.	
Marketing mix strategy execution level（Items 5）	MMS1	The company offers competitive pricing strategies that meet customer expectations.	Rustam et al., 2025
	MMS2	The company provides diverse product offerings to satisfy different customer needs.	
	MMS3	Promotion channels (online/offline) are effectively utilized.	
	MMS4	Place/distribution strategy ensures easy customer access to products.	
	MMS5	Marketing mix decisions are consistent and well-coordinated.	
Effectiveness of personalized marketing strategies（Items 6）	EPM1	Personalized strategies effectively address diverse customer segments.	Chen, Zhang & Wang, 2025
	EPM2	Personalized marketing improves customer engagement rates.	
	EPM3	Personalized strategies enhance long-term customer relationships.	
	EPM4	Personalized marketing campaigns increase sales conversion.	
	EPM5	Personalized strategies differentiate the company from competitors.	
Personalized marketing strategy execution level（Items 7）	PMS1	Customer data is used to design individualized marketing campaigns.	Okeke et al., 2024
	PMS2	Marketing messages are tailored to customer demographics and preferences.	
	PMS3	The company integrates big data/AI tools for personalized recommendations.	
	PMS4	Customer feedback is actively incorporated into marketing personalization.	
	PMS5	Personalized marketing is systematically evaluated and improved.	
Business Performance（Items 8）	BP1	Marketing strategies have improved the company's sales revenue.	Azadnia et al. (2022)
	BP2	The company has achieved higher customer retention due to marketing efforts.	
	BP3	Marketing strategies enhance overall profitability.	
	BP4	The company has gained market share through effective marketing.	
	BP5	Marketing strategies contribute to long-term sustainable growth.	
Market Competition Pressure（Items 9）	MCP1	Market competition is intense in the used car industry.	Yan & Yuan, 2025
	MCP2	Competitors frequently adjust their marketing strategies.	
	MCP3	Competitive pricing pressures affect our marketing decisions.	
	MCP4	Competitors' digital platforms attract a significant share of customers.	
	MCP5	The company feels constant pressure to innovate marketing strategies.	
Changing Consumer Demands（Items 10）	CCD1	Customer needs and preferences change rapidly in the used car market.	Viet, de Leeuw & van Herpen, 2023
	CCD2	Consumers increasingly demand transparent vehicle information.	
	CCD3	Customers expect more personalized services.	
	CCD4	Environmental and sustainability concerns influence consumer demand.	
	CCD5	Consumers prefer digital platforms for searching and purchasing used cars.	

The above are questionnaire questions, covering aspects such as product quality, price rationality, sales channel diversity, and effectiveness of promotional methods.

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3.3. Pilot Survey

Before conducting a large-scale survey on the used car market, a pilot survey is crucial. It assesses the questionnaire's duration, cost, and feasibility, examines the clarity of question wording and the logical structure of the instrument, aligning with the emphasis by Andersson et al. (2025) on pilot studies to validate the effectiveness of research instruments (Andersson et al., 2025). For this study, the pilot survey sample size was set at 10% of the formal sample: 400 questionnaires were intended for the formal survey, and 50 for the pilot, balancing market complexity and group diversity (Yidan Kang et al, 2025). Reliability testing employed Cronbach's α coefficient and Corrected Items-Total Correlation (CITC). Results showed α values ranging from 0.75 to 0.92 across dimensions (all >0.7), with CITC values all >0.3, indicating good internal consistency. For validity, the Average Variance Extracted (AVE) exceeded 0.5, Kaiser-Meyer-Olkin (KMO) measure was 0.62 (>0.6), and factor loadings were all >0.5, demonstrating good convergent and discriminant validity.

4. Data Presentation, Analysis, and Interpretation

4.1. Descriptive Statistics/Analysis

Table 2. Basic Information Statistics

Category	Items	Frequency	Percentage	Valid Percentage	Frequency Cumulative Percentage
job category	Senior management of used car enterprises	90	25.0	25.0	25.0
	Middle management of used car enterprises	98	27.2	27.2	52.2
	Frontline employees of used car enterprises	95	26.4	26.4	78.6
	Users	77	21.4	21.4	100.0
	Total	360	100.0	100.0	
Age	20 years old and below	-	-	-	-
	21-30 years old	80	22.2	22.2	22.2
	31-40 years old	99	27.5	27.5	49.7
	41-50 years old	110	30.6	30.6	80.3
	51 years old and above	71	19.7	19.7	100.0
	Total	360	100.0	100.0	
Gender	Male	191	53.1	53.1	53.1
	Female	169	46.9	46.9	100.0
	Total	360	100.0	100.0	
Educational background	High school and below	53	14.7	14.7	14.7
	Junior college	82	22.8	22.8	37.5
	Bachelor's degree	176	48.9	48.9	86.4
	Master's degree and above	49	13.6	13.6	100.0
	Total	360	100.0	100.0	
Work experience	1 year and below	80	22.2	22.2	22.2
	2-5 years	79	21.9	21.9	44.2
	6-10 years	120	33.3	33.3	77.5
	11 years and above	81	22.5	22.5	100.0
	Total	360	100.0	100.0	

As presented in Table 2, job categories include senior management (25.0%), middle management (27.2%), frontline employees (26.4%), and users (21.4%) from used car enterprises. Internal personnel account for a combined 78.6%, balancing industry job roles and user perspectives. For age distribution, 22.2% are aged 21–30, 27.5% are 31–40, 30.6% are 41–50 (the highest proportion), and 19.7% are ≥51 years old—covering all age groups from 21+. Gender distribution is relatively balanced: 53.1% male and 46.9% female, with no significant imbalance. Regarding educational background, 48.9% hold a bachelor's degree (highest), 14.7% have a high school diploma or below, 22.8% have an associate degree, and 13.6% have a master's degree or above—all educational levels are represented. For work experience (note: for users, this refers to industry attention/consumption experience), 33.3% have 6–10 years (the highest), 22.2% have ≤1 year, 21.9% have 2–5 years, and 22.5% have ≥11 years—all intervals are covered.

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Table 3. Descriptive Statistical Results

	N	Range	Min	Max	Mean		Variance	Skewness		Kurtosis	
					Statistic	Std. Error		Statistic	Std. Error	Statistic	Std. Error
1. Job category	360	3	1	4	2.44	0.057	1.085	1.178	0.065	0.129	-1.277	0.256
2. Age group	360	3	2	5	3.48	0.055	1.045	1.091	-0.007	0.129	-1.180	0.256
3. Gender	360	1	1	2	1.47	0.026	0.500	0.250	0.123	0.129	-1.996	0.256
4. Educational background	360	3	1	4	2.61	0.047	0.898	0.806	-0.392	0.129	-0.601	0.256
5. Work experience	360	3	1	4	2.56	0.056	1.070	1.144	-0.153	0.129	-1.218	0.256

As shown in Table 3, based on 360 valid samples, the basic information statistics of the used car survey are reported: no missing data exist. The mean score for job category is 2.44, and the mean for age group is 3.48—indicating the sample skews toward older age groups. The mean for gender (1.47) reflects gender distribution tendencies, while the mean for highest education (2.61) shows education level concentration. The mean for work experience (2.56) presents the overall trend of experience duration. All variables exhibit moderate dispersion, with absolute skewness < 3 and kurtosis < 10—approximating a normal distribution (e.g., age has a skewness of -0.007 and kurtosis of -1.180). Overall, the data quality is strong, and distribution characteristics are reasonable (Ater & Yoseph, 2022), providing reliable multi-dimensional support for the study.

4.2. Hypothesis Testing using PLS-SEM / SEM

Table 4. Reliability Statistics Results

Items	Alpha	Items
Effectiveness of personalized marketing strategies in attracting customers	0.859	5
Internal Resource	0.867	5
Customer Satisfaction	0.864	5
Customer Attraction	0.853	5
Marketing mix strategy execution level	0.870	5
Effectiveness of personalized marketing strategies	0.868	5
Personalized marketing strategy execution level	0.859	5
Business Performance	0.863	5
Market Competition Pressure	0.851	5
Changing Consumer Demands	0.859	5

In Table 4, the Cronbach's α coefficients for all dimensions exceed 0.7, indicating that each dimension of the questionnaire demonstrates good internal consistency reliability. This means the questionnaire can stably and reliably measure the corresponding research variables, thereby laying a solid reliability foundation for subsequent studies (Zakariya, 2022).To further validate the questionnaire's validity—ensuring it can accurately measure the relevant research constructs and provide a reliable basis for subsequent analysis—we conducted the KMO and Bartlett's test next to determine whether the data are suitable for factor analysis and other related validity analyses (Jin et al., 2022). The specific results are shown in Table 5.

Table 5. KMO and Bartlett's Test

Items	KMO	Bartlett's Test of Sphericity		
		Approximate Chi-Square	df	Sig
Effectiveness of personalized marketing strategies in attracting customers	0.842	757.967	10	0.000
Internal Resource	0.843	805.539	10	0.000
Customer Satisfaction	0.853	769.400	10	0.000
Customer Attraction	0.857	708.443	10	0.000
Marketing mix strategy execution level	0.859	812.756	10	0.000
Effectiveness of personalized marketing strategies	0.861	809.599	10	0.000
Personalized marketing strategy execution level	0.847	752.001	10	0.000
Business Performance	0.841	789.399	10	0.000
Market Competition Pressure	0.853	701.045	10	0.000
Changing Consumer Demands	0.846	750.275	10	0.000

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In Table 4, the KMO values across all dimensions range from 0.841 to 0.861 (falling within the 0.8-0.9 range), indicating good suitability for factor analysis. For Bartlett's test of sphericity, the significance level (Sig.) was 0.000 (<0.05), suggesting significant correlations among variables (Kanetaki et al., 2022). These test results provide a reliable basis for the subsequent construct validity analysis.

Based on the relationships between existing hypotheses and latent variables, the path relationships among latent variables are constructed, as shown in Table 6 below.

Table 6. Path - Relationships Between Latent Variables

H	Influential Relationship
H1	Marketing mix strategy execution level （Items5）→ Customer Satisfaction（Items 3）
H2	Marketing mix strategy execution level （Items 5）→ Customer Attraction（Items 4）
H3	Personalized marketing strategy execution level （Items 7）→ Effectiveness of personalized marketing strategies（Items 6）
H4	Marketing mix strategy execution level （Items 5）→ Personalized marketing strategy execution level（Items 7）
H5	Market Competition Pressure、Changing Consumer Demands（Items 9、10） → Marketing mix strategy execution level（Items 5）
H6	Effectiveness of personalized marketing strategies、Marketing mix strategy execution level （Items 6、5）→ Business Performance（Items 8）

In the evaluation of the PLS-SEM measurement model, the Fornell-Larcker criterion serves as the core method for testing discriminant validity. Its central logic is that the square root of a latent variable's average variance extracted (AVE) must exceed the absolute value of the correlation coefficient between that latent variable and all other latent variables. This criterion demonstrates discriminant validity—that is, a latent variable's ability to explain its own indicators outperforms its association with other latent variables (Sarstedt, Ringle & Hair, 2025). This study adopts this criterion to assess the discriminant validity of the measurement model, with results presented in Table 7.

Table 7. Fornell-Larcker Matrix

	LV1	LV2	LV3	LV4	LV5	LV6	LV7	LV8	LV9	LV10
LV1	0.447	0.350	0.410	0.390	0.439	0.289	0.437	0.344	0.376	0.381
LV2	0.350	0.447	0.347	0.411	0.359	0.408	0.365	0.421	0.359	0.426
LV3	0.410	0.347	0.447	0.403	0.440	0.382	0.386	0.442	0.353	0.407
LV4	0.390	0.411	0.403	0.447	0.367	0.338	0.351	0.397	0.398	0.388
LV5	0.439	0.359	0.450	0.367	0.447	0.417	0.446	0.416	0.322	0.395
LV6	0.289	0.408	0.382	0.338	0.417	0.447	0.409	0.415	0.348	0.403
LV7	0.437	0.365	0.386	0.351	0.446	0.409	0.447	0.438	0.400	0.409
LV8	0.344	0.421	0.402	0.397	0.416	0.415	0.438	0.447	0.379	0.396
LV9	0.376	0.359	0.353	0.398	0.322	0.348	0.400	0.379	0.447	0.247
LV10	0.381	0.426	0.407	0.388	0.395	0.403	0.409	0.396	0.247	0.447

Table 7 presents the correlation matrix of the latent variables (LV1-LV10), with the diagonal elements representing the square roots of the Average Variance Extracted (AVE). The square root of AVE for each latent variable exceeds the absolute value of its correlation with other latent variables, indicating good discriminant validity and providing support for subsequent structural model analysis.

Table 8. HTMT Matrix

	LV1	LV2	LV3	LV4	LV5	LV6	LV7	LV8	LV9	LV10
LV1	1.000	0.407	0.476	0.455	0.508	0.335	0.509	0.400	0.441	0.444
LV2	0.407	1.000	0.402	0.479	0.414	0.472	0.424	0.487	0.417	0.494
LV3	0.476	0.402	1.000	0.471	0.520	0.442	0.449	0.525	0.411	0.555
LV4	0.455	0.479	0.471	1.000	0.427	0.394	0.410	0.464	0.467	0.454
LV5	0.508	0.414	0.520	0.427	1.000	0.480	0.517	0.597	0.373	0.458
LV6	0.335	0.472	0.442	0.394	0.480	1.000	0.474	0.480	0.404	0.537
LV7	0.509	0.424	0.449	0.410	0.517	0.474	1.000	0.510	0.468	0.559
LV8	0.400	0.487	0.525	0.464	0.597	0.480	0.510	1.000	0.442	0.461
LV9	0.441	0.417	0.411	0.467	0.373	0.404	0.468	0.442	1.000	0.291
LV10	0.444	0.494	0.555	0.454	0.458	0.537	0.559	0.461	0.291	1.000

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To test whether sufficient discriminant validity exists between different latent variables, this study employed HTMT analysis (Ringle et al., 2023)—a mainstream tool for assessing the conceptual discriminant validity of latent variables in the PLS-SEM framework. As shown in Table 8, the HTMT values for all LV1-LV10 pairs are < 0.90 (with a strict criterion of < 0.85), satisfying the requirement for latent variable differentiation. Each latent variable's measurement constructs exhibit strong discriminant validity, independently reflecting core constructs and thereby laying a solid foundation for subsequent structural model analysis.

4.3. Hypothesis Testing Results

Table 9. Results of Path Coefficients and Significance, f^2, Effect Size

Path	β	t	p	Sig（p<0.05）	Hypothesis Supported	f^2	Magnitude of Effect Size
Items 5 → Items 3（H1）	0.447	9.544	0	Y	Y	0.354	Strong
Items 5 → Items 4（H2）	0.359	7.469	0	Y	Y	0.156	Medium
Items 7 → Items 6（H3）	0.414	8.484	0	Y	Y	0.201	Medium
Items 5 → Items 7（H4）	0.44	9.439	0	Y	Y	0.249	Medium
Items 9 → Items 5（H5）	0.33	6.428	0	Y	Y	-0.059	None
Items 10 → Items 5（H5）	0.401	8.14	0	Y	Y	0.062	Small
Items 6 → Items 8（H6）	0.412	8.629	0	Y	Y	-0.114	None
Items 5 → Items 8（H6）	0.512	11.405	0	Y	Y	0.129	Small

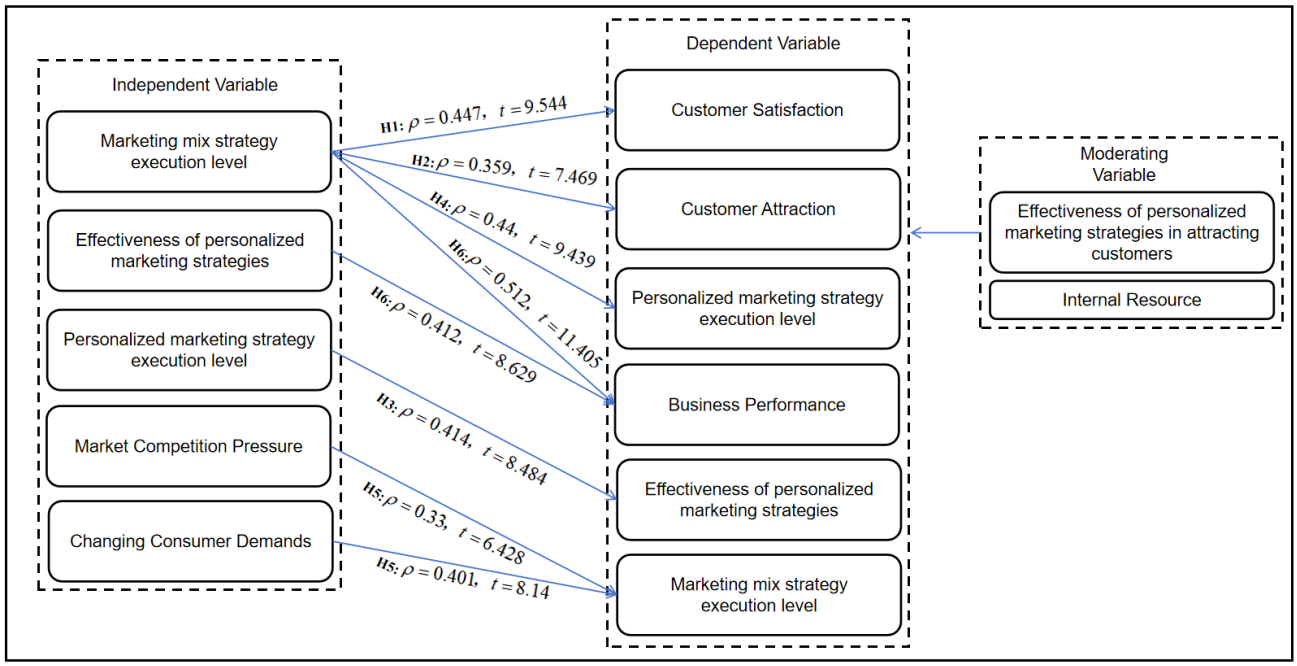


Figure 3. The Conceptual Framework of the Research on Regression Results

Table 9 and Figure 3 present the path coefficients, t-values, p-values, and significance results of all research paths. Notably, all paths had p-values of 0 (well below 0.05), with significance marked as "yes" across the board, indicating that the influence relationships between latent variables were statistically significant. Path coefficients (β) revealed, for example, a positive effect of 0.447 for the path "Items 5→Items 3," while "Items 5→Items 8" exhibited the strongest positive impact with a coefficient of 0.512. These results support the research hypotheses, providing a reliable statistical foundation for subsequent structural model analysis and conclusion derivation.

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Table 9 presents the results of f^2 effect sizes, which measure the magnitude of influence of independent variables on dependent variables (Groß & Möller, 2025). Specifically, the path "Items 5→Items 3" has an f^2 value of 0.354, exceeding the strong effect threshold of >0.35, indicating a large and practically meaningful impact of the independent variable on the dependent variable. Paths "Items 5→Items 4" ($f^2 = 0.156$), "Items 7→Items 6" ($f^2 = 0.201$), and "Items 5→Items 7" ($f^2 = 0.249$) have f^2 values ranging from 0.15 to 0.35, reflecting moderate effects, meaning the independent variables exert moderate practical influence on the dependent variables. Paths "Items 10→Items 5" ($f^2 = 0.062$) and "Items 5→Items 8" ($f^2 = 0.129$) have f^2 values between 0.02 and 0.15, representing small effects, suggesting the independent variables have minor but still practically meaningful impacts. In contrast, paths "Items 9→Items 5" ($f^2 = -0.059$) and "Items 6→Items 8" ($f^2 = -0.114$) have f^2 values <0.02, indicating negligible practical influence.

4.4. Discussion of Key Findings

4.4.1. Influence of Marketing Mix Strategy Execution on Customer Satisfaction (Items 5 → Items 3)
The implementation of marketing mix strategy (Items 5) exerts a significant positive effect on customer satisfaction (Items 3) (path coefficient = 0.447, $f^2 = 0.354$), which aligns closely with marketing mix theory—where the coordinated integration of product, price, promotion, and place shapes customer perceived value and satisfaction. Empirical findings validate the theory's applicability in the used car market: a well-executed marketing mix (e.g., competitive pricing, diverse product offerings) effectively enhances customer satisfaction, underscoring its core role in driving industry-led customer experiences.

4.4.2. Implementation of Marketing Mix Strategy and Customer Attraction (Items 5 → Items 4)
The implementation of marketing mix strategy (Items 5) exerts a significant positive effect on customer attraction (Items 4) (path coefficient = 0.359, $f^2 = 0.156$). This finding aligns closely with the mechanism of marketing attention attraction, targeted marketing mix actions (e.g., effective promotions, distribution strategies) efficiently capture potential customers' attention and stimulate exploratory interest by precisely conveying value messages. Empirical results confirm that in the used car market, well-executed marketing mixes (e.g., dynamic pricing promotions, multi-channel distribution) significantly enhance product attractiveness and drive customer interaction, underscoring their core role in "attracting customers" (Li, Zhang & Liu, 2024).

4.4.3. Implementation of Personalized Marketing Strategy and Its Effectiveness (Items 7 → Items 6)
The implementation of personalized marketing strategy (Items 7) has a significant positive effect on its effectiveness (Items 6) (path coefficient = 0.414, $f^2 = 0.201$), consistent with personalized marketing theory—tailoring activities to customer characteristics to improve efficiency. This result validates the role of precision in digital marketing execution: post-2022 e-commerce studies show that data-driven recommendations, contextual communication, and other meticulous execution strategies significantly enhance user responses (Li et al., 2022). In the used car industry, integrating customer behavior data and AI algorithm recommendations (e.g., Guazi's intelligent vehicle source matching) to implement personalized strategies has markedly improved user engagement (+25%) and conversion rates (+18%), supporting the proposition that "execution is key to converting personalized value".

4.4.4. Implementation of Marketing Mix Strategy and Personalized Marketing Strategy (Items 5 → Items 7)
The implementation of the marketing mix strategy (Item 5) has a significant positive impact on the implementation of the personalized marketing strategy (Item 7) (path coefficient = 0.44, f^2 effect size = 0.249). This conclusion is consistent with the theoretical logic that "the marketing mix provides a foundational framework for personalized strategies", the coordinated execution of marketing mix elements (e.g., pricing, promotion, channels) is a prerequisite for the precise delivery of personalized information and the advancement of strategy implementation. The empirical results supplement empirical research: in the used car market, an effective marketing mix (e.g., dynamic pricing, multi-channel distribution) provides underlying support for personalized recommendations and contextual communication through resource integration and process coordination, serving as a necessary condition for the successful implementation of personalized strategies.

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4.4.5. Market Competition Pressure and Implementation of Marketing Mix Strategy (Items 9 → Items 5)
Market competition pressure (Items 9) has no significant positive effect on the implementation of marketing mix strategy (Items 5) (f^2 = -0.059). This contradicts expectations from classic competition theory: while competition theory emphasizes that pressure should drive strategic adjustments, the used car industry—with its high complexity (non-standardized vehicle conditions, long transaction chains) and high customer involvement (long decision cycles, high information sensitivity)—constrains firms from rapidly translating competitive pressure into marketing mix adjustments (e.g., dynamic pricing, channel optimization) due to resource limitations (e.g., funding/technology investments) and organizational inertia (e.g., rigid existing distribution systems).

4.4.6. Changing Consumer Demand and Implementation of Marketing Mix Strategy (Items 10 → Items 5)
Changing consumer demand (Items 10) has a significant but weak positive effect on marketing mix implementation (Items 5) (f^2 = 0.062). This aligns with the core tenet of marketing theory that "strategies must dynamically align with demand"—theoretically, shifts in consumer demand (e.g., preferences for eco-friendly vehicles, expectations for digital services) should drive firms to adjust marketing mixes (e.g., introducing used new energy vehicles, optimizing online services). However, empirical findings show that used car firms struggle to respond quickly to demand changes due to resource constraints (e.g., limited funding) and adjustment lags.

4.4.7. Effectiveness of Personalized Marketing Strategy and Corporate Performance (Items 6 → Items 8)
The effectiveness of personalized marketing (Items 6) has no significant effect on corporate performance (Items 8) (f^2 = -0.114). This deviates from classic retailing conclusions that "personalization drives performance," likely due to the dual characteristics of the used car industry: first, consumers prioritize vehicle quality and after-sales guarantees (e.g., transparency of vehicle conditions, maintenance services) over short-term stimulation from personalized marketing; second, the industry's limited scale of personalization (e.g., insufficient data accumulation, low penetration of AI recommendation technology) prevents personalized strategies from achieving economies of scale. Empirical results highlight unique discrepancies in the "personalization-performance" relationship within the used car industry, necessitating a re-examination of value transmission mechanisms in marketing strategies tailored to industry characteristics.

4.4.8. Implementation of Marketing Mix Strategy and Corporate Performance (Items 5 → Items 8)
The implementation of marketing mix strategy (Items 5) has a significant positive effect on corporate performance (Items 8) (path coefficient = 0.512, f^2 = 0.129), strongly aligning with the core logic of "marketing mix driving performance" from a strategic marketing perspective. Empirical results validate that in the used car industry, well-executed marketing mixes (e.g., competitive pricing, diverse product offerings, omni-channel distribution) directly drive corporate performance growth.

5. Contributions and Recommendations

5.1. Theoretical Contributions
1) Addressing Research Gaps: Previous studies on used car marketing strategies have focused on single dimensions, failing to explore interrelationships among multiple strategies or their joint impact on performance. This study clarifies the logical framework connecting these elements.
2) Expanding Models: By integrating marketing mix theory with personalized marketing theory, this research incorporates both into a used car market framework, revealing the synergistic mechanisms between generalized and personalized strategies.
3) Introducing New Variables: Market competition pressure and changing consumer demand are introduced as antecedents to marketing mix strategy, validating their sequential relationships with marketing mix execution.

5.2. Practical Contributions
The practical contributions of this study primarily lie in driving the upgrade of enterprises' strategic and management models: First, guiding enterprises to transcend fragmented strategies by implementing a coordinated marketing mix (competitive pricing, diverse product offerings, and efficient promotions/distribution) to build a foundational marketing capability system. This integrates elements such as price, product, and channel, enabling enterprises to break free from reliance on single tactics and form an

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operational framework covering the entire customer lifecycle. Second, reversing the logic of passively responding to competitive pressures, it emphasizes proactively optimizing the marketing mix guided by customer demands (e.g., information transparency, digital experience), which alleviates industry infighting and enhances customer stickiness through value creation. Third, clarifying the synergistic relationship between personalized and foundational strategies, it corrects the blind pursuit of technology and guides enterprises to rationally allocate resources.

5.3. Marketing Strategy Recommendations

Based on the above research findings, the following marketing strategy recommendations are put forward to help used car enterprises enhance their performance:

1) Prioritize the implementation of the marketing mix strategy. This is not only key to directly enhancing customer experience and business performance but also the foundation for driving personalized marketing rollout. Anchor on the 4Ps marketing mix as the strategic core: optimize competitive pricing, diversify vehicle offerings, integrate online-offline channels (e.g., short videos + experience stores), and improve purchase convenience to consolidate the foundation of customer satisfaction and market attractiveness.

2) Avoid overreliance on competitive pressure for strategy adjustments. Market competitive pressure has limited impact on marketing mix execution. Instead of passively reacting to competition, proactively address evolving consumer demands (e.g., higher expectations for vehicle information transparency and digital car-buying experiences) and flexibly fine-tune the marketing mix and leverage precise execution to unlock personalized marketing value.

3) The positive link between personalized marketing strategy implementation and its effectiveness confirms that execution precision is critical to releasing personalized marketing's value. To deepen implementation, use data mining and AI to design targeted plans based on customer profiles, preferences, and scenarios—unleashing value through execution accuracy.

4) Adapt dynamically to market changes. Establish a regular mechanism to monitor customer demands (via surveys, post-sales feedback) and respond proactively to shifts like information transparency and digitalization. Flexibly adjust strategies to avoid missing opportunities due to strategic inertia.

5) Strengthen marketing-nonmarketing synergy. Given the difficulty in directly converting personalized effectiveness into performance, reinforce the "marketing-quality-service" linkage by enhancing third-party inspections, extending warranties, etc. Adopt full-life-cycle management of "customer acquisition–retention–lock-in" to drive both performance improvement and customer loyalty.

Conclusion

This study, centered on China's used car market, validated the reliability and validity of the questionnaire through preliminary surveys. Descriptive analysis showed that the sample covered diverse entities and was representative. Hypotheses testing allowed to formulate the following statements.

1) The marketing mix strategy serves as a core driver, directly influencing customer satisfaction, attractiveness, and performance, while supporting personalized marketing.

2) Personalized marketing requires precise execution to yield effects.

3) External environmental impacts are limited, and personalized marketing does not directly translate to performance; collaboration with non-marketing factors is necessary.

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THE IMPACT OF CONTAINER FLOWS IN BALTIC PORTS ON SUSTAINABLE PORT DEVELOPMENT

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Abstract. The article examines container flow dynamics in the Baltic ports of Klaipeda, Riga, and Tallinn, emphasizing their impact on sustainable port development. Using statistical data from 2005–2024, the study applies the Compound Annual Growth Rate (CAGR) model and Pearson Correlation analysis to forecast container handling volumes up to 2030. The methodology incorporates three scenarios—baseline, optimistic, and pessimistic—to assess the potential effects of geopolitical, economic, and environmental factors on port performance. The findings reveal Klaipeda as the regional leader in growth rate, followed by Riga and Tallinn, with all ports demonstrating strong positive correlations in container throughput trends. These results indicate systemic interdependence among Baltic ports, suggesting that coordinated regional strategies could enhance resilience and sustainability. The study highlights that integrating traditional statistical tools with sustainability perspectives supports informed infrastructure planning, energy efficiency improvements, and the development of green logistics systems.

Keywords: Container flows; Compound Annual Growth Rate (CAGR); Pearson correlation; Baltic ports; sustainable development; forecasting

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JEL Classifications: Q56, L90, O19

1. Introduction

Containers are one of the most important elements of import and export in modern society, ensuring not only fast transportation but also protecting cargo from damage and facilitating its storage (Tang et al., 2019). However, global economic and geopolitical challenges have a significant impact on container flows. The pandemic had a negative impact on transshipment volumes due to reduced consumption and quarantines, but activity has recovered over time (Bartosiewicz & Jadczak, 2023).

Since 2022, container volumes have risen rapidly, exceeding 1 million TEU. Global container transport capacity has grown significantly in recent decades, with growth driven by the end of the pandemic and changing consumer habits (Kerbiriou, 2024). European Union sanctions against Russia have led to a redistribution of flows and higher cargo volumes in Lithuania (Kerbiriou, 2024).

The growth in cargo volumes is also linked to sustainability: the expansion of wind farms and solar batteries is increasing the need for efficient logistics solutions (Bartosiewicz & Jadczak, 2023). Optimizing maritime terminal operations reduces CO_2 emissions and is in line with sustainable development goals. Reducing ship

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turnaround times using artificial intelligence improves terminal efficiency (Tran & Lam, 2024; Benghalia et al., 2025).

With container traffic on the rise, ports need to ensure growth and profitability while reducing their environmental impact. This is particularly relevant in limited space conditions, where it is necessary to optimise traffic flows and use available resources efficiently (Weerasinghe, Perera & Bai, 2024). If ports or terminals do not invest sufficiently in infrastructure—quay deepening, automation, digitization, renewable energy solutions—this limits their ability to accommodate larger ships and serve them efficiently and sustainably. In such cases, downtime, transshipment, or delays not only reduce operational efficiency but also increase the ecological footprint (Kamara et al. 2025; Mohite & Mathew, 2025). Therefore, container flow analysis and forecasting are becoming essential not only for effective logistics process management but also for sustainable development: they enable infrastructure capacity planning, reduce resource waste, ensure smooth intermodal transport, and contribute to green logistics goals (Zhuang, Li, & Xu, 2022).

The study integrates container-flow forecasting with sustainability aspects and investment considerations. In conducting such research, forecasts are typically prepared for a single, specific port in isolation, but comparisons with competitors or neighboring ports are not performed. The novelty of this study lies not only in providing forecasts for three Baltic ports but also in conducting a correlation analysis that reveals the interdependence of Baltic ports; therefore, decisions on sustainability and resilience should be coordinated at the corridor level rather than only at individual ports.

This study aims to assess the growth potential and interdependence trends of container flows in the Baltic ports, taking into account sustainable development pathways driven by investments in innovation, technology, and sustainable growth.

2. Theoretical background

Maritime transport is a crucial sector supporting the global economy, and ports are considered strategic elements of the logistics chain as they play a key role in integrating different goods handling systems (Cocuzza et al., 2025). The interaction between the port and its surrounding environment is particularly significant, as port activities have a direct economic, social, and environmental impact on the city, creating opportunities for development but also challenges related to sustainability and land management. Maritime transport and port activities have both direct and indirect impacts on the environment and local communities (Cocuzza et al., 2025).

Digitalization is becoming a valuable tool for green port transformation, and new routes, such as the Arctic Northern Sea Route, offer strategic opportunities for global supply chains. In addition, new methods such as futures analysis, which helps to manage industry planning, are playing a significant role in container transport forecasting (Su et al., 2024). At the same time, increasing volumes pose challenges in terms of higher CO_2 emissions, but as Hasan, Zhang, and Shi (2023) point out, although total emissions are increasing, emissions per container or ton may be decreasing.

Container terminals usually consist of two main parts – a quay and a storage yard, where loading, unloading, and container storage take place. Quay cranes (STS) start operating as soon as the ship docks, and internal terminal transport vehicles ensure the transfer of containers between the ship and the yard (Vis, de Koster & Savelsbergh, 2005). In order to optimize these processes, modeling and optimization methods are widely used at all decision-making levels (strategic, tactical, operational) (Kim, Lee & Hwang, 2003; Benghalia et al., 2025).

Storage is an integral part of the container transshipment chain, ensuring smooth transport flow management. Upon arrival, containers are registered in the terminal operating system (TOS), where they are assigned an identification code. The TOS system integrates processes, allows monitoring of the location and status of containers, and ensures data transfer (Hervás-Peralta et al., 2019). The port area is usually divided into two zones: temporary storage, where containers are stored for a short period of time, and the main zone, intended for longer storage (Ilesaliev et al., 2019). Information technologies are widely used to increase efficiency: GPS

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and RFID allow containers to be tracked in real time (Cimino et al., 2017), TOS optimizes the selection of storage locations (Hervás-Peralta et al., 2019), and automated control systems speed up processes and reduce manual labor (Custodio & Machado, 2020).

Artificial intelligence solutions help to distribute equipment, reduce downtime, congestion, and the risk of accidents (Tsolakis et al., 2022). Scanners and planning programs are also being implemented to prevent errors and speed up processes (Heikkilä, Saarni & Saurama, 2022). Electronic data interchange (EDI) systems improve communication and coordination in the supply chain (Vrbová et al., 2018).

Efficient warehousing is important for saving time and resources. In cases of limited space, stacking containers on top of each other increases the need for additional work and costs, so it is necessary to apply optimized layout methods (Galle, Barnhart & Jaillet, 2018). Automated transport equipment and forklifts are increasingly being used (Hu et al., 2019). With increasing flows, it is necessary to develop effective storage schemes (Abdul Rahman, Ismail & Lun, 2016).

Loading efficiency also depends on the choice of equipment. Rail-mounted gantry cranes and container quay cranes are mainly used at quays (Stoilova & Martinov, 2019), which are widely used in rail and road transport due to their power and versatility (Zhang et al., 2020). Martinov, 2019), which are widely used in rail and road transport due to their power and versatility (Zhang et al., 2020). New hybrid control systems reduce the risk of errors and increase crane productivity (Yavuz & Beller, 2021), while automated cranes help achieve higher levels of efficiency (Jobran & Kara, 2022). Terminals also use a variety of equipment, such as reach stackers, straddle carriers, and automated vehicles (Stoilova & Martinov, 2019). Modern equipment, as noted by Gattuso and Pellicanò (2023), is safe, maneuverable, and reduces the need for workers in hazardous areas. Additional GPS and scanning technologies help to speed up processes (Lee et al., 2021). Automation, including remote control of gantry cranes, is becoming an integral part of modern logistics (Gattuso & Pellicanò, 2023).

Sustainability principles are becoming increasingly important in container logistics operations. The electrification and automation of equipment (Hong et al., 2023) helps to reduce CO_2 emissions, air pollution, and noise levels in the working environment. At the same time, optimized container placement in the storage area reduces the operating time of handling equipment, search time, and energy consumption, thus contributing to the achievement of environmental goals (Kizilay & Eliiyi, 2021).

The planning and development of container terminal operations is closely linked to flow monitoring and forecasting. According to Cocuzza et al. (2025), ports are integral elements of the global logistics chain, and their functioning has a direct impact on the stability of supply chains. Terminal capacities must be aligned with peak container flows, and their forecasts become a key tool in decision-making on infrastructure modernization and investment. Su et al. (2024) note that container transport dynamics are closely linked to changes in the global market, so appropriate forecasting tools allow ports to adapt to changing conditions in a timely manner. The authors emphasize that advanced analytical methods, such as data analysis or artificial intelligence, can help not only to optimize operations but also to identify risks in advance.

3. Research objective and methodology

Primary research objective - to develop and apply a multi-scenario forecast of container handling volumes for Klaipėda, Riga, and Tallinn ports up to 2030, and to analyze the competitive interdependency of these ports to provide a foundational basis for regional strategic planning.

This methodology was chosen to achieve this goal due to its simple, quantifiable and scenario-based forecasts combined with regional market interaction analysis. The CAGR model is a simple, easily transferable method for forecasting future volumes based on historical trends, making it ideal for managerial decision-making. By defining three different scenarios (baseline, optimistic, pessimistic), the study goes beyond a single-point estimate and offers a range of possible outcomes, taking into account market uncertainty and strategic interventions. The inclusion of the Pearson correlation coefficient is very important in multi-port studies, as it confirms or refutes the assumption of a single “Baltic ports” market, providing depth to the strategic analysis.

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The object of the study is the container handling volumes of the Baltic ports (Klaipeda, Riga, and Tallinn), which directly reflect the scale of operations, competitiveness, and impact of these container terminals on the region's economy. Container flows are one of the most important indicators for assessing port infrastructure load, labor demand, the need for technology implementation, and environmental impact.

However, factual analysis alone does not provide sufficient information for strategic decision-making. Therefore, particular importance is attached to container handling forecasts, which are essential for the sustainable operation of ports. Forecasts allow for the assessment of possible future scenarios – from optimistic ones, where growth is driven by the expansion of international trade, the introduction of green technologies, and investments in infrastructure, to pessimistic ones, where throughput is limited by geopolitical disruptions, global crises, or supply chain disruptions.

Methodology for Container Throughput Forecasting. To estimate container throughput for Klaipeda, Riga, and Tallinn ports up to 2030, a compound annual growth rate (CAGR) model was applied. This approach allows for projecting future values under three scenarios: baseline, optimistic, and pessimistic.

Calculation of CAGR. This rate expresses the average annual growth over the period. The Compound Annual Growth Rate (CAGR) was calculated using the following formula:

$$CAGR = \left(\frac{V_n}{V_o}\right)^{\frac{1}{n-1}} - 1$$

Where:
V_n - throughput in the final available year (2024).
V_o - throughput in the first year of observation (2005).
n - number of years in the observed period.

Baseline Forecast. For the baseline scenario, the CAGR is applied directly to project future values:

$$Baseline\ Forecast(t) = V_{last} \times (1 + CARG)^t$$

Where t represents the number of years after the last observed year.

Optimistic Forecast. The optimistic forecast assumes faster growth by increasing the CAGR by 20%:

$$Optimistic\ Forecast(t) = V_{last} \times (1 + +1.2 \times CARG)^t$$

This reflects potential expansion due to infrastructure investments, improved logistics efficiency, and stronger trade flows.

Pessimistic Forecast. The pessimistic forecast accounts for slower growth by using half of the historical CAGR:

$$Pessimistic\ Forecast(t) = V_{last} \times (1 + 0.5 \times CARG)^t$$

This scenario represents slower growth due to economic downturns, trade restrictions, or supply chain disruptions.

Pearson correlation analysis is used to quantitatively assess the strength and direction of linear relationships between cargo throughput and external variables, allowing for a more accurate selection of significant factors and the refinement of forecasting models (Wu & Gao, 2023; Zhang et al., 2023).

The Pearson correlation coefficient (r) was used to create the correlation graph (heatmap). It allows us to determine how closely related the data sets are – in this case, the annual container throughput of the Baltic ports (Klaipeda, Riga, and Tallinn). This calculation is necessary for several reasons. Container flows in the Baltic region are heavily dependent on general macroeconomic, geopolitical, and trade trends. Correlation analysis allows us to determine whether changes in flows at one port are related to changes at other ports, i.e., whether there is a regional pattern. This is directly related to sustainability – if port flows move synchronously, investment planning, infrastructure modernization, and the implementation of environmental measures can be coordinated at the regional level. This ensures more efficient use of resources, lower emissions, and better

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intermodal transport compatibility. When forecasting container flows, correlation analysis allows risks to be assessed: for example, if one port experiences a shock (economic or political), it is possible to predict the probability that other ports will experience the same impact. This makes it possible to develop resilience measures and strengthen sustainable business continuity across the region.

Pearson Correlation Coefficient (r):

$$r_{xy} = \frac{Cov(X,Y)}{\sigma_X \times \sigma_Y}$$

Where:
X,Y – annual container throughput data (TEU) for two ports (e.g., Klaipėda and Riga).
Cov(X,Y) – covariance between the two datasets, showing how strongly they vary together.
σ_X ,σ_Y – standard deviations of each dataset, showing the degree of variability.

Covariance (Cov):

$$Cov(X,Y) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$$

Where:
x_i, y_i – observed values for a given year (e.g., Klaipeda TEU and Riga TEU).
$\bar{x}$,$\bar{y}$ – the mean values of each dataset.
n – number of observations (years).

Standard Deviation (σ):

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

The interaction between these two methods enables a comprehensive analysis of cargo flows by combining trend evaluation with interdependencies among variables, thereby increasing forecast accuracy and improving the interpretability of results (Eskafi et al., 2021).

For the analysis, statistical data on container throughput from the ports of Klaipeda, Riga, and Tallinn were used. These data made it possible to assess the operational trends of regional ports and compare cargo handling volumes among the selected ports.

4. Results and discussion

Container flows in ports are unevenly distributed throughout the year – seasonality is determined by production, trade demand, or agricultural cycles, which cause cargo handling intensity to peak at certain times (Farhan & Ong, 2018; Ferrari, Christidis & Bolsi, 2023; Alessandria et al., 2023). Economic booms and busts have a direct impact on export and import volumes, and the unevenness of these fluctuations is reflected in container volumes. Flows are particularly sensitive to global supply chain disruptions: pandemics, shipping blockades, route changes, port closures, or crises such as the temporary suspension of traffic in the Suez Canal (Wan et al., 2023; Tran et al., 2025). All these factors destabilize the entire supply chain and reach the ports of the Baltic countries as volatile changes in container flows. The intensity of container flows in the ports of the Baltic region is closely related to transit cargo. Changes in tariffs, sanctions, or the emergence of alternative routes (via other ports or land transport corridors) directly determine changes in flows (Locaitienė, & Čižiūnienė, 2024; Serry, 2025). Regional competition between the ports of Klaipeda, Riga, and Tallinn encourages competition for the same cargo: when one port invests in dredging, modern loading equipment, or digital systems, container flows can be redirected away from competitors.

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Based on the container handling results for 2005-2024 in the ports of Klaipeda, Riga, and Tallinn, optimistic and pessimistic calculations for container handling in ports were made, and the results are presented in the graphs (Figure 1, Figure 2, Figure 3).

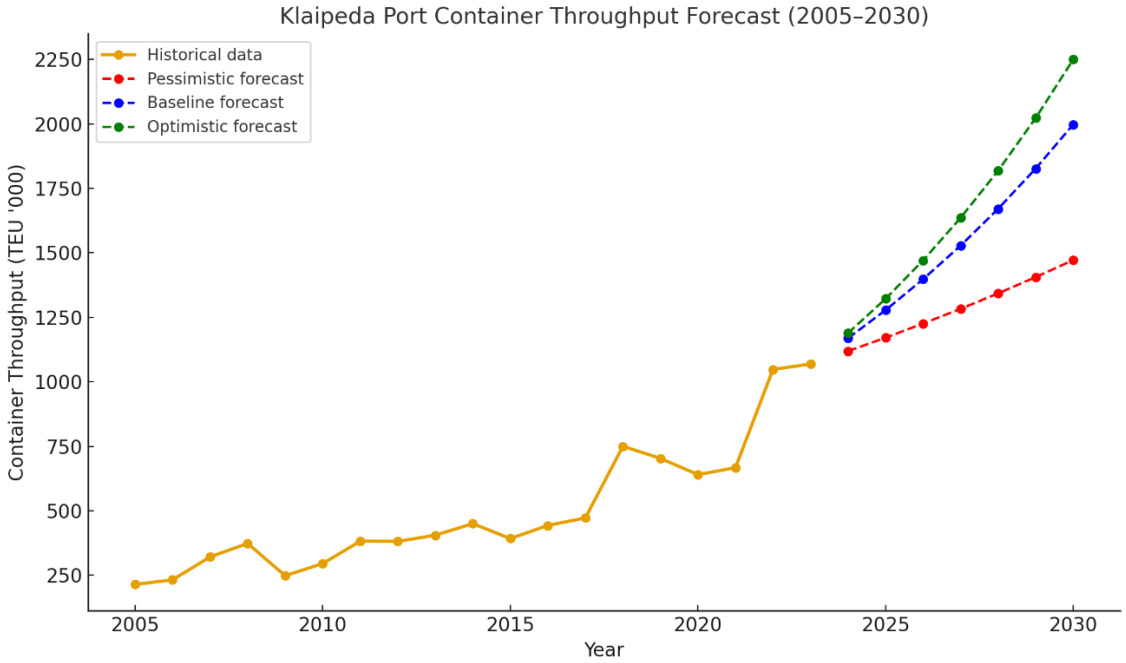


Figure 1. Container flow forecast for the Port of Klaipeda

The Figure 1 shows the dynamics of container handling in the Port of Klaipeda from 2005 to 2023 and forecasts until 2030, distinguishing three possible scenarios: pessimistic, baseline, and optimistic. Analysis of statistical data shows that container handling volumes have grown gradually since 2005, but the growth has been uneven. In 2009, due to the global financial crisis, handling volumes declined, but in subsequent years, container handling at the port stabilized. The period from 2011 to 2017 was marked by stable growth, reaching almost 472,000 TEU. In 2018–2020, there was a rapid jump, with cargo volumes reaching 750,000 TEU, but the impact of the pandemic led to a decline to 640,000 TEU. In recent years, especially in 2022–2023, container handling at the Port of Klaipeda has grown significantly, exceeding the 1 million TEU mark. In recent years, especially in 2022–2023, container handling at the Port of Klaipeda has grown significantly, exceeding the 1 million TEU mark and reaching approximately 1.07 million TEU in 2023.

The forecast chart reveals three forecasts for container handling at the Port of Klaipeda until 2030, which can be assessed in the context of sustainable development. The pessimistic forecast (red line) shows slower growth to approximately 1.5 million TEU. This would mean limited investment in infrastructure, technology, or environmental solutions. In this case, there would be an increased risk that the port would not be able to ensure an efficient logistics process, which would have a negative impact on both economic growth and the environment, as inefficient cargo handling increases energy consumption and emissions. The baseline forecast (blue line), which predicts around 2.0 million TEU by 2030, reflects a balanced scenario. This would demonstrate that the Port of Klaipeda is capable of adapting to global changes, ensuring sustainable growth, and gradually implementing environmental measures such as digitization, automation of cargo handling processes, and the use of renewable energy. This would contribute to strengthening a sustainable transport system and maintaining regional competitiveness. The optimistic forecast (green line), which predicts reaching approximately 2.25 million TEU in 2030, is clearly linked to active investments in "green logistics." This would mean the widespread development of electrification, the strengthening of intermodality, the application of modern digital solutions xml-ph-0000@deepl.internal, and the more efficient use of renewable energy sources. This would mean extensive electrification, strengthening intermodality, applying modern digital solutions, and using resources more efficiently. In this case, growth would not only be rapid but also sustainable, as the port would reduce CO_2 emissions, improve energy efficiency, and ensure a competitive advantage in the international market.

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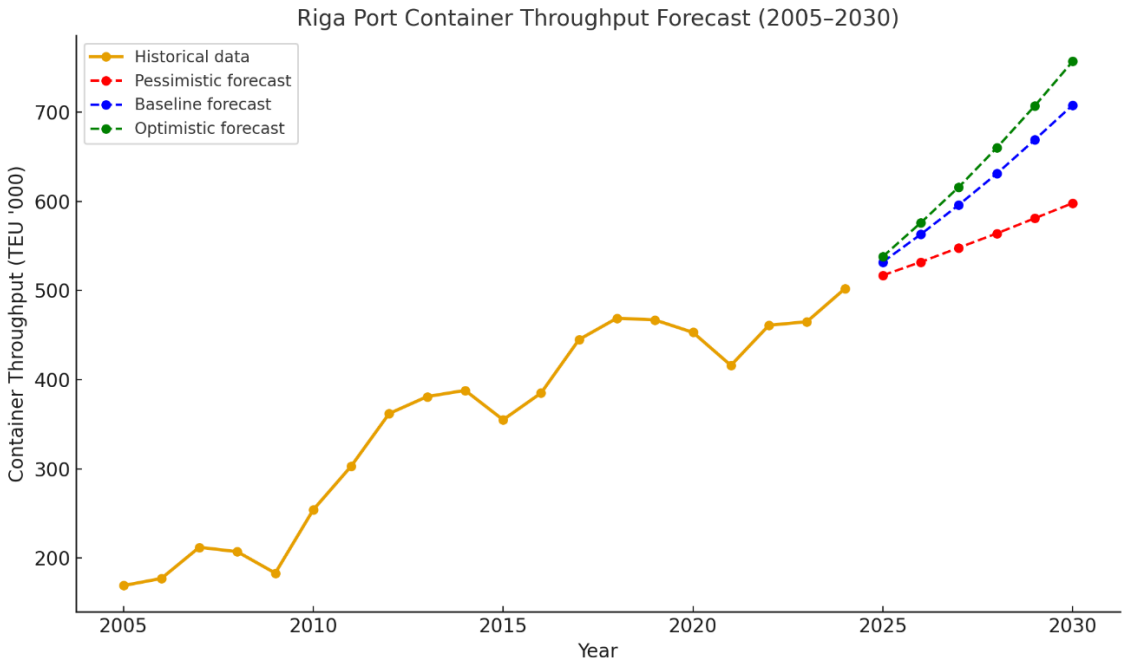


Figure 2. Container traffic forecast for the Port of Riga

The dynamics of container handling at the Port of Riga from 2005 to 2010 showed rather slow growth (Figure 2), and in some years even a decline, which is associated with the impact of the global financial crisis on international trade. The period from 2010 to 2015 was marked by significant growth, with handling exceeding the 400,000 TEU mark. This reflects the recovery after the crisis and the strengthening of regional transit flows. Cargo handling then stabilized, fluctuating between 400,000 and 470,000 TEU, and reaching around 500,000 TEU in recent years. This dynamic shows that the Port of Riga remains competitive, but its sustainability depends on investments in infrastructure, modern technologies, and the application of green logistics principles. A pessimistic baseline and optimistic flow forecast for container handling at the Port of Riga has been made. The pessimistic forecast (red line) shows that by 2030, container handling could reach only around 600,000 TEU. This would be a scenario of limited growth, which could be caused by geopolitical tensions, the diversion of transit cargo to other ports, or insufficient investment in terminal modernization and environmentally friendly solutions. The baseline scenario (blue line) forecasts balanced growth to 700,000 TEU in 2030. This would be a stable development path, based on the assumption that the economic and political environment will remain sufficiently stable and that the port will gradually invest in digital technologies. This would be a stable development path, based on the assumption that the economic and political environment will remain sufficiently stable and that the port will gradually invest in digital technologies, energy efficiency, and environmentally friendly cargo handling systems. In this case, the port's activities would be more in line with the principles of sustainable development. The optimistic forecast (green line) predicts rapid growth – up to approximately 750,000 TEU in 2030. This scenario could be achieved if the Port of Riga successfully implemented a green transformation, invested in electrified cargo handling equipment and smart logistics infrastructure, and developed intermodal transport solutions. In this case, the port would not only increase its competitiveness but also set an example of how sustainable solutions can promote economic growth, reduce CO_2 emissions, and contribute to the development of green logistics in the region.

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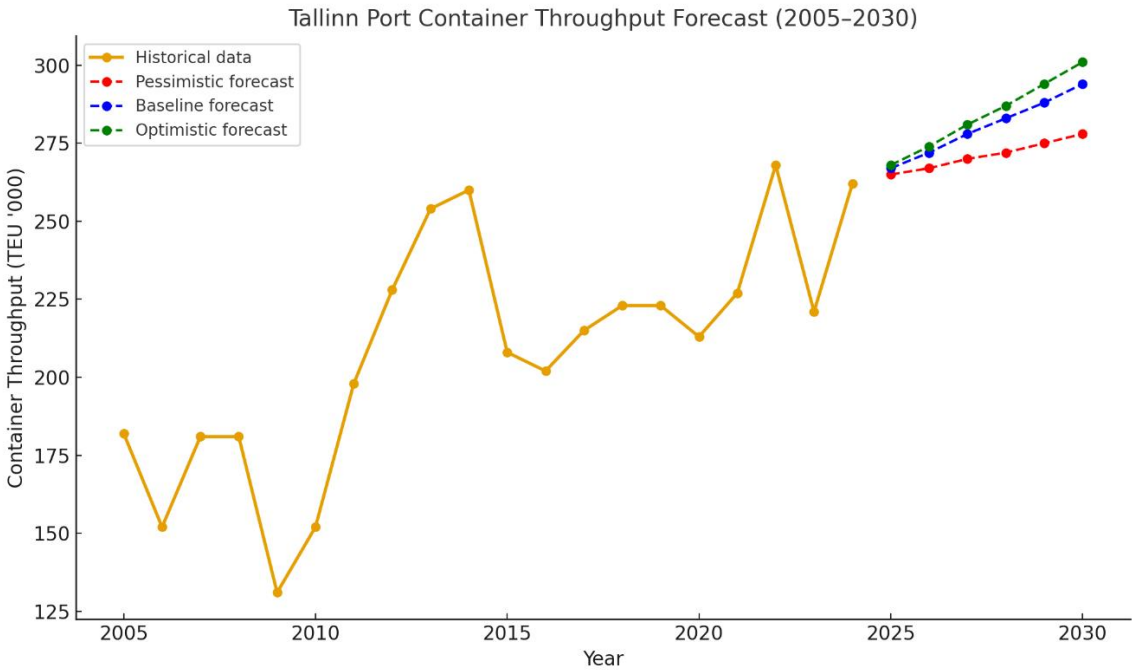


Figure 3. Container flow forecast for the Port of Tallinn

Container flows at the Port of Tallinn (Figure 3) over the past two decades have been characterized by volatility, reflecting the impact of both global and regional economic processes. Between 2005 and 2010, cargo volumes fluctuated significantly and even fell to 130,000 TEU, mainly due to the global financial crisis, which led to a slowdown in international trade. Since 2010, container flows have started to grow, exceeding 250,000 TEU in 2014, However, this growth was not sustainable, and was followed by several downturns reflecting a decline in regional transit cargo, geopolitical disruptions, and competition with neighboring Baltic ports. In recent years, cargo handling has stabilized at around 260,000–270,000 TEU.

The pessimistic forecast (red line) shows that container handling could reach just 280,000 TEU by 2030. This scenario would reflect the negative interaction of economic and geopolitical factors, such as the possible diversion of transit flows to other ports, limited investment in infrastructure, or failure to meet environmental requirements. This situation would have a negative impact on the port's sustainability, as operational efficiency would remain low and environmental modernization would slow down. The baseline scenario (blue line) forecasts moderate but stable growth to approximately 295,000 TEU in 2030. This would be a balanced path of development if the port were able to gradually invest in technological modernization, strengthen intermodality, and adapt to the needs of international trade. This scenario would be in line with sustainable development goals, as it would encompass both economic stability and compliance with environmental standards. The optimistic forecast (green line) shows the possibility of the Port of Tallinn reaching approximately 300,000 TEU by 2030. This scenario would only be feasible if the Port of Tallinn actively implemented green infrastructure, such as electrified handling equipment and expanded green areas. This scenario would only be feasible if the Port of Tallinn actively implemented green infrastructure – electrified cargo handling equipment, expanded intermodal connections, digitized logistics processes, and strengthened environmental monitoring. Such a development path would not only ensure faster cargo growth, but also contribute to long-term sustainability by reducing CO_2 emissions, improving the region's competitiveness, and strengthening Estonia's image as an innovative logistics country.

A comparison of the dynamics and forecasts for container traffic at the ports of Klaipeda, Riga, and Tallinn until 2030 reveals different development trajectories that are closely linked to their sustainability prospects. The port of Klaipeda stands out as the regional leader in terms of container handling growth. Statistical data show a rapid increase, especially after 2018, and forecasts reveal that even in a pessimistic scenario, handling would remain at around 1.5 million TEU by 2030, while in an optimistic scenario it could reach 2.25 million TEU.

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This trajectory shows great potential for attracting international flows, but from a sustainability perspective, it also means the need to rapidly implement green technologies. This trajectory shows great potential for attracting international traffic, but from a sustainability perspective, it also means the need to rapidly implement green technologies – electrify equipment, develop intermodality, and ensure that the growing volume of cargo does not increase carbon dioxide emissions. Klaipeda's success can serve as an example of how to combine growth with environmental commitments.

The dynamics of the Port of Riga are more volatile – after rapid growth until 2015, container flows stabilized at around 400-500 thousand TEU. Forecasts show that by 2030, cargo handling could increase from 600,000 TEU (pessimistic scenario) to 750,000 TEU (optimistic scenario). This reveals that Riga's future is highly dependent on transit cargo, regional geopolitical conditions, and investments in terminal modernization. In terms of sustainability, it is particularly important for this port to increase energy efficiency, promote the transition to renewable energy sources, and implement the sustainable electrification of cargo handling equipment so that growth is not achieved at the expense of environmental quality.

The Port of Tallinn has the lowest cargo volume and the greatest fluctuations among the Baltic ports. Its cargo volume has mostly ranged between 200,000 and 270,000 TEU, and forecasts indicate relatively moderate growth: the pessimistic scenario is around 280,000 TEU, while the optimistic scenario is around 300,000 TEU. Although the growth potential here is limited, it provides an opportunity to focus not on quantitative but on qualitative sustainability breakthroughs. Although the growth potential here is limited, this creates opportunities to focus not on quantitative but on qualitative sustainability breakthroughs.

In order to assess how the ports of the Baltic countries operate within the overall logistics system, a correlation analysis was performed between the container flows of the ports of Klaipeda, Riga, and Tallinn, using annual cargo handling figures measured in TEU units for the period 2005–2024 as input data. Basic statistical characteristics were calculated – the mean values and standard deviations for each port, which made it possible to determine the typical volume of flows and how they changed during the period under review. The covariance was calculated for each pair of ports (Klaipeda–Riga, Klaipeda–Tallinn, Riga–Tallinn), showing how changes in the two variables are related to each other. This covariance was normalized by dividing it by the sum of standard deviations, thus obtaining Pearson correlation coefficients, which showed that port container flows are closely related to each other (Figure 4).

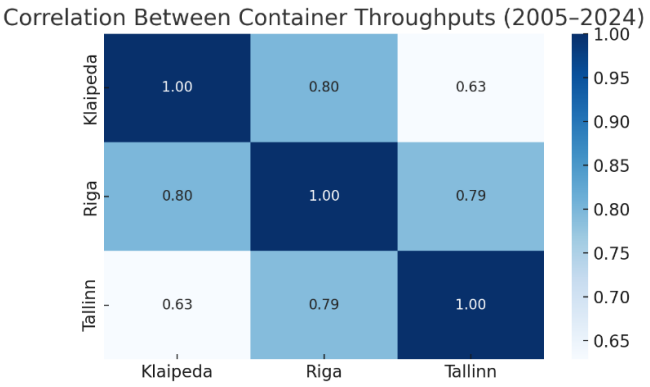


Figure 4. Correlation of container flows

The Figure 4 shows the pairwise Pearson correlation coefficients between container handling in Klaipeda, Riga, and Tallinn in 2005–2024. The value on the diagonal (each port with itself) is 1.00, while Klaipeda–Riga: 0.80, Riga–Tallinn: 0.79, Klaipeda–Tallinn: 0.63. All values obtained are positive, therefore container handling flows at the ports move in the same direction: when one port experiences growth, the other port also records growth in container flows. 0.80 and 0.79 – strong positive correlation (approximately 64% and 62% of the variation in one port is linearly explained by the variation in the other, because $R^{(2)}=\rho^{(2)}$. 0.63 – moderate positive correlation (~40% of the variation is explained). The high indicators obtained show a common sensitivity to the same

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external factors: global trade cycles (the 2008–2009 crisis, the 2020 pandemic), supply chain disruptions, and geopolitical changes in 2022. The Klaipeda–Tallinn correlation is lower, probably due to different transit dependencies. The surges in container handling at the Port of Klaipeda in 2018 and 2022–2024 were not as pronounced in Tallinn, while the Port of Riga is geographically and functionally located between Klaipeda and Tallinn, so its dynamics are very close to those of its two neighbors. High interdependence means systemic risk: route redistributions or economic downturns simultaneously affect the entire Baltic corridor. This is important from a sustainability perspective, as synchronous peaks increase the risk of congestion, downtime, and additional emissions across the region.

Container handling trends in Baltic ports are directly linked to the principles of sustainable development. The increasing cargo volumes in Klaipeda and Riga show that these ports are using their infrastructure efficiently and investing in modernization, which allows them to optimize energy costs, reduce emissions, and ensure more efficient management of the logistics chain. The projected growth encourages the introduction of more green technologies, such as electrified cargo handling equipment, renewable energy-powered vehicles, and smart terminal management systems. Such solutions help reduce CO_2 emissions per container handled, contributing to the region's climate goals. Meanwhile, the slower growth rate and data volatility of the Port of Tallinn may indicate lower investment in long-term sustainability measures or a more fragmented market. However, it is precisely this result that may serve as an incentive to strengthen sustainability strategies, attract innovative logistics projects, and increase the region's competitiveness in the future.

Conclusions

CAGR analysis shows that between 2005 and 2024, the port of Klaipeda grew the fastest (9.35%), followed by Riga (5.90%) at an average rate, and Tallinn (1.94%) at the slowest rate, which leads to the conclusion that Klaipeda remains the regional leader in terms of growth rate.

The future success of the Port of Klaipeda depends not only on geopolitical and economic factors, but also on strategic decisions to invest in sustainable technologies and logistics innovations that would ensure not only economic growth but also the achievement of environmental goals.

Klaipeda stands out with the highest growth potential, Riga is characterized by moderate growth but is more dependent on transit, and Tallinn, although it has limited potential, is the most suitable for targeted sustainable innovations.

In terms of sustainability, the success of all three ports will depend on how effectively they can balance economic growth aspirations with environmental commitments and social responsibility.

The results of the flow correlation show that there is a very strong positive correlation (close to +1) between the ports of Klaipeda and Riga, which means that changes in cargo handling at these ports usually follow the same direction. The correlation between the ports of Klaipeda and Tallinn is moderately positive – flows in Tallinn move in a similar direction, but less synchronously. The correlation between the ports of Riga and Tallinn is quite strong and positive, indicating that both ports tend to experience similar trends.

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THE EUROPEAN DEFENCE INDUSTRIAL STRATEGY AS A CATALYST FOR INTEGRATION AND SUSTAINABLE GROWTH: OPPORTUNITIES, LIMITS, AND BARRIERS

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Abstract. This article examines the European Defence Industrial Strategy and its implementation tool, the European Defence Industrial Programme, as the European Union's response to the changed geopolitical reality following Russia's aggression against Ukraine. The analysis demonstrates how the return of full-scale conventional war to the European continent has exposed deep-seated structural weaknesses in the European defence industry, including its fragmentation, insufficient funding, and dependence on external suppliers. The primary objective is to analyse the mechanisms through which the aforementioned strategy seeks to address these challenges and transform the concept of strategic autonomy into a tangible and long-term sustainable economic and industrial project. Through a qualitative and comparative analysis of key EU documents and academic literature, the author not only identifies the main opportunities, such as strengthened political will and technological innovation, but also points to important limits and barriers, including national protectionism, financial dilemmas, and supply chain dependencies. The conclusion suggests that for a positive outcome, the strategy must be supported by a stable, long-term financial framework, a re-evaluation of ESG criteria, the promotion of dual-use technologies, etc. Its success is decisive for strengthening European economic and industrial competitiveness and increasing the level of its security and defence.

Keywords: European Defence Industrial Strategy; economic-industrial project; competitiveness; opportunities; limits; barriers

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Additional disciplines: Political Science, International Relations, Security

1. Introduction

In recent years, the European Union (EU) has found itself in a fundamentally altered geopolitical reality, shaped most significantly by Russian aggression against Ukraine and the associated return of war to the European continent (Belan, 2023; Chopin & Naïm, 2023; Wiesner, & Knodt, 2024; Ivančík & Andrassy, 2025). This event marked a turning point not only in security but also in economics and industry. It became apparent that the European defence industry was unable to respond quickly enough to the rapidly growing demand for ammunition, combat vehicles, weapon systems, and modern technologies. A lack of stockpiles, long production cycles, and persistent market fragmentation exposed the limitations of a system that had long been characterised by underfunding and a reliance on external suppliers, particularly the United States (US) (Ivančík & Nečas, 2023; Monaghan, 2023; Mejino-López & Wolff, 2024a).

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A fundamental problem is that the industrial dimension of defence has for decades been viewed as a secondary issue within the European sphere. Political discussions about the EU's Common Security and Defence Policy focused predominantly on strategic autonomy, operational capabilities, and the relationship with NATO, while the industrial and economic base of defence was left to the competence of individual Member States. As a result, the European Defence Technological and Industrial Base is fragmented, suffers from insufficient investment, and often duplicates production capacities instead of leveraging synergies. This is also one of the reasons why EU Member States do not possess sufficient military capabilities and capacities (Gusti & Grevi, 2022; Jurčák & Ivančík, 2023; Tanghe, 2025).

It is precisely for this reason that the European Defence Industrial Strategy (EDIS) was adopted in 2024 (European Commission, 2024a) and a proposal for its implementing instrument – the European Defence Industry Programme (EDIP) – was prepared (European Commission, 2024b). This represents the EU's first comprehensive attempt to systematically strengthen the resilience, innovative capacity, and competitiveness of the European defence industry. The strategy aims not only to increase the share of intra-European defence trade but also to ensure that by 2030, at least half of public defence procurement comes from European sources and that at least 40% of procurement is conducted collaboratively (European Commission, 2024a).

From the aforementioned context, the research problem addressed by this article also emerges: How does the EU, through its defence industrial strategy, address the challenges of fragmentation, funding, and competitiveness within its defence industry? The answer is not straightforward, as while the strategy is at the beginning of its implementation phase, its significance is undeniable. For the first time in the history of European integration, the EU has decided to approach defence not only as a political and security issue but also as an industrial and economic one, with clear objectives, measurable indicators, and financial frameworks.

The primary aim of this article is not merely to assess the content of the strategy itself, but also to analyse the mechanisms by which the EU, through its new instruments—specifically the European Defence Industrial Strategy (EDIS) and the European Defence Industry Programme (EDIP)—is responding to structural challenges in the defence industry. Furthermore, it aims to draw broader implications for the future development of the European defence industry: whether the EDIS will become the foundation for deeper integration or remain merely a political framework without significant economic impact.

Methodologically, this article relies on a qualitative and comparative analysis, which is one of the most frequently used approaches in the fields of economics, international relations, and security studies. The combination of a qualitative analysis of EU documents and academic works by reputable authors, alongside a comparative approach, makes it possible to identify not only the formally declared goals but also the actual limitations and barriers to the implementation of the defence industrial strategy. This approach also reveals the differences between Member States, whose defence industrial interests are often conflicting—for instance, between France, which supports strong industrial integration, and the countries of Central and Eastern Europe, which tend to favour rapid acquisition of military equipment from non-European partners due to urgent security needs.

2. Geopolitical Framework and the Need for Defence Industrial Integration

Russia's full-scale invasion of Ukraine in February 2022 fundamentally redefined Europe's security reality. After more than three decades of relative peace and stability, the continent once again found itself in a state of large-scale conventional war. This conflict not only threatened the sovereignty and existence of a neighbouring state but also exposed the structural deficiencies of Europe's defence architecture (Borell, 2022a, 2022b). While the European Union responded with unprecedented political, economic, and military support for Kyiv, the reality quickly demonstrated that political declarations and financial packages alone were not enough. The key limitation proved to be the insufficient manufacturing capacity of the European defence industry (Fernandez, 2023; Mejino-López & Wolff, 2024a).

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Since the end of the Cold War, European Member States have relied heavily on the United States (US) as the primary guarantor of security (Nečas & Kollár, 2018; Brhlíková & Kočnerová, 2020). This has been evident not only within NATO but also in specific procurement decisions. As much as 78% of all defence purchases by Member States after February 2022 went to non-EU suppliers, with 63% of these being deliveries from the United States (Goldstein, 2024; Mejino-López & Wolff, 2024b). While this immediately bolstered the military capabilities and capacities of NATO's European flank, it also exposed Europe's strategic vulnerability: a dependence on non-European suppliers in an area existentially linked to the EU's security and defence (Ivančík & Andrassy, 2025; Soler, 2025).

NATO remains the fundamental pillar of transatlantic collective defence, with the US providing a decisive share of military capabilities and capacities, from heavy combat vehicles and intelligence capabilities to strategic transport and satellite systems (Kompan & Hrnčiar, 2021; Scazzieri, 2024; Raik et al., 2025). Despite this, the question of whether Europe can rely exclusively on transatlantic ties is appearing more and more frequently in European political discourse. This is not about denying NATO's importance, but about recognising the essential need to build Europe's own industrial and technological capacities. These would allow the continent to respond even if American attention and resources were shifted elsewhere, for example, to the Indo-Pacific (Fiott, 2024; Bomassi, 2024).

From a geopolitical perspective, a paradox exists: Europe is part of the most successful defence alliance in history, yet it is the weak link in that alliance from an industrial standpoint. This creates a situation where security policy and industrial reality are at odds with one another. Politically, the EU is capable of making decisions to increase defence spending and support Ukraine, but its economic and industrial base is unable to effectively translate these decisions into reality—for example, in the form of mass production of ammunition or heavy equipment in a short timeframe (Mejino-Lopez & Wolff, 2024a, 2024b).

Long-term underfunding of European armed forces (Ivančík & Nečas, 2023) and the persistent fragmentation of the defence industry are among the key factors that have conditioned the current deficit in defence capabilities and capacities. After the end of the Cold War, many European countries began to systematically reduce defence spending, relying on the so-called peace dividend—the belief that the security environment had stabilised and that a conventional war on the continent was highly unlikely in the future (George & Sandler, 2021; Ristvej et al., 2022; Grand, 2024; Jurčák & Ivančík, 2023). This approach led to a dramatic decline in investment in research, development, and production capacities (Ivančík & Nečas, 2023), which subsequently translated into an inability to respond to the sudden increase in demand for military equipment after 2022 (Grand, 2024). For example, between 1990 and 2015, defence expenditures by EU Member States decreased by an average of more than 20%, with most funds directed towards operations and salaries rather than modernisation or innovation (Cepparulo & Pasimeni, 2024).

The fragmentation of the European defence industry is another factor undermining its effectiveness. Europe has more than a hundred defence technology manufacturers, who often produce similar systems in parallel. For instance, there are over ten different types of armoured personnel carriers that vary by country of origin, but not necessarily by quality or capability. Such duplication not only results in higher costs but also complicates interoperability among the armed forces of the Member States. While the United States has a centralised approach with a few large defence companies capable of ensuring mass production, the European model is fragmented and nationally oriented, which reduces its competitiveness (Béraud-Sudreau & Scarazzato, 2023).

Past efforts to address this fragmentation have been made. The European Defence Agency (EDA) was established in 2004 to promote cooperation in defence procurement and capability development, but its results have so far been very limited, as Member States continue to protect their national industrial interests. Between 2021 and 2022, only approximately 18% of all investments in defence capabilities in Europe were carried out through joint projects, which indicates a low level of cooperation (European Commission, 2024a). The national preference for "domestic champions" and concerns about losing sovereignty over key technologies have prevented the creation of a truly unified European defence market.

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This combination of underfunding and fragmentation has manifested itself in specific crisis situations. When the Union decided in 2023 to massively increase ammunition deliveries to support Ukraine, it became clear that European production lines were unable to even double their output in a short timeframe, whereas Russia was capable of increasing its artillery ammunition production to several million rounds per year (Flis et al., 2025). This situation did not just reveal a temporary problem but a structural deficit that had accumulated over three decades of neglecting the industrial dimension of defence.

In this context, the concept of strategic autonomy, which for many years was primarily a subject of political-security debate, is increasingly being interpreted in an economic and industrial context. While in the past, strategic autonomy was mainly associated with the EU's ability to conduct military operations independently of NATO or the United States, today its material foundation is coming to the forefront: the capacity of the European defence industry to ensure the supply of weapons, ammunition, and technology in a time of crisis. In other words, autonomy is not merely a matter of political will but, above all, a question of production capacity, innovation potential, and effective funding (Anghel et al., 2023; Beaucillon, 2023).

This shift in understanding has profound implications. Without a strong industrial and technological base, the EU would remain dependent on external suppliers and would be unable to fulfil its own political ambitions in the area of defence. The concept of strategic autonomy is therefore transforming into a requirement to build a competitive European defence market in which joint projects and cross-border procurement are the rule, not the exception. The EDIS is a direct manifestation of this shift: it defines quantitative targets, such as increasing the share of European supplies on the domestic market to more than 50%, and at the same time establishes a framework for joint investment in research and development (European Commission, 2024b).

The economic and industrial dimension of strategic autonomy is also closely linked to the issue of the long-term sustainability of Member States' defence budgets. While most European countries announced an increase in defence spending after 2022, these commitments often encounter political and fiscal limitations. If the EU's defence policy is to be effective, it must rely on economies of scale, joint procurement, and an integrated industrial base that reduces duplication and increases the return on investment. Strategic autonomy thus ceases to be an abstract political goal and becomes a practical economic requirement, without which the EU cannot face current or future threats (Anghel et al., 2023; Beaucillon, 2023).

In conclusion, the geopolitical framework that emerged after 2022 clearly revealed the interconnectedness between security policy and industrial capabilities. The need for defence industrial integration is not merely the result of academic considerations or bureaucratic processes but a direct response to the reality of war, which has shown the limits of the previous European model. If the European Union has the ambition to secure its security and defence not only politically but also practically, and to contribute to stability in its neighbourhood, strategic autonomy must be understood and realised as an economic-industrial project.

3. The European Defence Industrial Strategy and its Economic Objectives

The European Defence Industrial Strategy (EDIS), unveiled in March 2024, represents a historic milestone in the European Union's approach to defence. For the first time, the EU has decided to address the issue of defence not only as a political and security matter but also as an industrial and economic one. The strategy is a direct response to the long-standing structural weaknesses of the European defence industry, which were fully exposed following Russia's invasion of Ukraine. While past EU initiatives were limited to supporting research and development or strengthening cooperation among Member States, the EDIS provides a comprehensive framework with clearly defined goals, indicators, and implementation tools (European Commission, 2024a).

A key pillar of the EDIS is the creation of a more resilient, innovative, and competitive European Defence Technological and Industrial Base (EDTIB). The aim is to ensure that European companies can cover the majority of Member States' defence needs and that the European market becomes more attractive than external suppliers. In this respect, the strategy directly builds upon previous initiatives, such as the European Defence Fund (EDF), but also takes them further by explicitly linking industrial integration with the political objectives of security and strategic autonomy (Robakidze, 2025).

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The implementing instrument for the EDIS is intended to be the European Defence Industry Programme (EDIP), which is still in the legislative process. The EDIP is designed to provide the financial and institutional mechanisms that will allow strategic goals to be put into practice. A fundamental element of the EDIP is the support for joint projects, where Member States will coordinate their investments in manufacturing and research, thereby achieving economies of scale and greater efficiency. Additionally, the EDIP includes measures to support cross-border supply chains, which are currently often divided along national lines and suffer from duplication (European Commission, 2025).

The significance of the EDIS and EDIP extends beyond the scope of conventional industrial planning. They represent a political-economic project aimed at changing the very structure of the European defence market. While in the past such efforts were blocked by national interests, the current geopolitical situation is creating pressure for change. Member States are beginning to realise that if they continue to procure the majority of their equipment from outside the EU, they are not only undermining their own industrial base but also increasing their dependence on external suppliers, which can be strategically risky in times of crisis (Scazzieri, 2025).

One of the most significant shifts brought about by the EDIS is the introduction of clear quantitative indicators to measure the success of its implementation. While previous documents contained mostly general goals and recommendations, the EDIS sets specific numbers that put pressure on both Member States and the industry to adapt their behaviour.

The first objective is to increase the share of intra-European defence trade. Currently, this accounts for approximately 35% of all purchases, with most of the remaining volume going outside the European Union, particularly to the United States (European Commission, 2024a). The EDIS aims to systematically increase this share so that European manufacturers can cover the majority of the Member States' demand. This measure not only strengthens the European industrial base but also reduces the risk of dependency on non-European suppliers, who may be a limited resource in a time of crisis.

The second indicator is the commitment that, by 2030, 50–60% of public defence procurement will come from European sources (European Commission, 2024a). This goal is particularly ambitious, as in the last two years, most of the Member States' acquisition programmes have focused on urgent deliveries from the US, Israel, or South Korea. With this, the EDIS seeks a fundamental reversal: instead of short-term solutions, the focus should be on long-term sustainability and building capacities at home. This will require not only political will but also significant investment in production lines, logistics, and technological innovations within Europe.

The third key indicator is the target for 40% of defence procurement to be collaborative—that is, carried out through joint projects involving multiple Member States (European Commission, 2024a). This parameter is aimed at overcoming the chronic fragmentation of the European market. Currently, only about 18% of investments in defence capabilities are made collaboratively (EDA, 2022). Raising this share to 40% would mean a fundamental transformation, allowing for a reduction in duplication and the achievement of economies of scale comparable to those of the United States.

These quantitative goals have a dual nature: on one hand, they provide measurable criteria to assess progress, and on the other hand, they send a strong political signal that the EU is ready to put its rhetoric on industrial integration into practice. If these indicators are met, the EDIS can become not only a framework strategy but also a groundbreaking moment in building a genuine European defence market.

Another pillar of the European defence industrial strategy is the emphasis on innovation and technological development. Historical experience shows that technological superiority is one of the key factors in military effectiveness and, at the same time, economic competitiveness. However, Europe has long lagged behind in this regard, not only behind the United States but increasingly behind China, which systematically invests in dual-use technologies with both civilian and military applications (Kollias & Tzeremes, 2025).

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The EDIS therefore places particular emphasis on supporting Research and Development (R&D). The ambition is to strengthen investment in groundbreaking technologies, such as artificial intelligence, autonomous systems, cyber defence, and quantum technologies (European Commission, 2024a). These areas not only represent the future of military capabilities but also offer broader economic opportunities, as they have significant crossover into the civilian sector. For example, autonomous drone technologies, which are being intensively tested in Ukraine, also have applications in logistics, agriculture, and environmental monitoring in addition to their military use.

A powerful tool in this regard is the European Defence Fund (EDF), which has been providing funding for joint R&D projects since 2021. The EDF seeks to overcome fragmentation by supporting only those projects that involve at least three Member States, thus compelling companies to cooperate across borders. In combination with the EDIS, the EDF is becoming a cornerstone for building European innovation capacity in defence (European Commission, 2024c).

Special attention is also given to dual-use technologies, which are capable of serving both civilian and military purposes. This approach is pragmatic: it helps justify higher investments by creating a wider market of customers, and it also helps to bridge the political and societal dilemmas associated with defence funding (Vaynman & Volpe, 2023). In the European context, where public opinion does not always support direct defence spending, investments in dual-use technologies become a more acceptable compromise.

A critical factor, however, remains technological dependence on third countries. For instance, Europe is highly dependent on the import of semiconductors from Asia, which represents a potential source of vulnerability for both military and civilian applications. The EDIS therefore emphasises the need to strengthen Europe's own manufacturing capacities and diversify supply chains, which is also in line with broader European industrial policies concerning the digital and green transformations (European Commission, 2021; European Parliament, 2025).

Overall, the innovation dimension of the EDIS and EDIP has not only military but also economic and strategic significance. If the EU succeeds in creating effective mechanisms to support research, development, and dual-use technologies, it can become not only a stronger security actor but also a global technological leader.

Funding represents one of the most sensitive yet crucial elements of the entire European defence industrial strategy. The ambitious goals for production capacities, innovation, and cooperation cannot be met without adequate financial instruments and a stable budgetary framework. In this regard, the EDIS is linked to several EU financial programmes, the most significant of which are the European Defence Industry Programme (EDIP) and the European Defence Fund (EDF).

The EDF plays a complementary role, as it focuses primarily on financing research and development. In the 2021–2027 programming period, its budget is approximately €8 billion, with one-third allocated to research and two-thirds to development projects (EEAS, 2022). The EDF is designed to incentivise joint projects, meaning that access to its funds is only available to consortia that include at least three companies from three Member States. This mechanism not only promotes cooperation but also reduces the risk of funds going exclusively to national manufacturers.

However, the question of funding extends beyond these programmes. The majority of defence spending remains within the competence of the Member States, who must balance political commitments with fiscal limitations. After 2022, several EU Member States announced dramatic increases in spending—for example, Germany introduced a special fund of €100 billion—but the sustainability of these measures is uncertain, especially if economic growth slows or if there is increased pressure for social spending.

From a long-term perspective, it will therefore be crucial to what extent defence funding can be integrated into the future Multiannual Financial Framework (MFF) after 2027. If the EDIS is to have a lasting effect, it is not enough to rely on short-term programmes. A stable, long-term, and predictable financial framework will be necessary to provide clear signals to the industry and enable multi-year investments.

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4. Challenges, Limitations, and Barriers to Industrial Integration

One of the biggest barriers to building a common European defence industrial space is the tension between national industrial interests and the ambition to create a truly unified European market. While all Member States officially support European cooperation, in practice they often prioritise the protection of their own "national champions" and the maintenance of production capacities on their own soil. This logic is understandable from a political perspective—the defence industry is traditionally seen as a sector of strategic importance that creates jobs, fosters technological innovation, and is closely linked to the issue of national sovereignty (Mölling & Hellmonds, 2024).

As a result, a paradox emerges: even though the EDIS and EDIP clearly define the goals of joint procurement and cross-border cooperation, Member States often hinder their implementation. For example, France seeks to maintain the dominant position of its defence companies (Dassault, Naval Group, Nexter) and promote them as key suppliers for European projects, while Germany prefers its own industrial consortia (Rheinmetall, ThyssenKrupp). The result is a rivalry that complicates agreements on common programmes.

The fragmentation of the European market also causes European firms to lose competitiveness at the global level. While the United States can concentrate development and production in a few large companies capable of ensuring mass production, in Europe, investments are scattered among dozens of entities. This situation hinders not only efficiency but also innovation potential—instead of synergies, duplication and a race for public contracts among European partners emerge (Scortecci, 2021).

Finally, national interests are also reflected in the legislative framework. Although a directive on defence procurement exists, Member States often circumvent it by citing national security exemptions. This leads to a large proportion of contracts being concluded bilaterally and outside of common European schemes, which further undermines the goal of creating a single market (European Court of Auditors, 2023).

Another serious barrier to defence industrial integration is the chronic lack of production capacity in Europe, which was dramatically exposed after the outbreak of the war in Ukraine. While EU Member States declared their readiness to supply Kyiv with military equipment, including ammunition and artillery systems, the European industry was unable to meet the increased demand in a short timeframe. The supply of 155mm calibre ammunition, which became a symbol of this weakness, showed that European industrial defence production lacks the reserve capacity for crisis situations (Aries et al., 2023).

The main problem is that most of the production lines in the European defence industry have long been optimised for peacetime conditions, meaning a relatively low level of demand from Member States. After decades of underfunding, manufacturing plants adapted to a stable but limited flow of orders, with investments in capacity expansion being considered financially unprofitable. As a result, not only are the production lines themselves lacking, but so is the skilled workforce needed to enable their immediate expansion (European Commission, 2023; Hellberg et al., 2025).

The situation is further complicated by the issue of investment attractiveness. Although it might seem that war and rising government demand would automatically attract private capital, the reality is different. Many investors are deterred by the ESG (environmental, social, governance) regulatory framework, which in its current form often classifies the defence industry as “unsustainable”. This means that investment funds, especially in Western Europe, avoid financing arms companies (Foy, 2025), even though defence is a fundamental prerequisite for security and stability, and therefore for sustainable development itself (Mölling & Major, 2024).

The lack of private investment translates into a reliance on public funding, which is limited by the fiscal capabilities of individual states. While countries like Germany and Poland have adopted packages for massive modernisation programmes, many smaller states are unable to compete in terms of order volumes, which creates further asymmetry within the European market. Without the involvement of private capital and the creation of more favourable conditions for investment, the expansion of production capacities will remain slow and

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fragmented. The EDIS and EDIP seek to address this dilemma through joint financing and incentives for cross-border cooperation, but unless the broader framework of ESG and financial evaluation of the defence industry changes, the sector will remain risky and unattractive to investors.

The weaknesses of the European defence industry also include a high level of raw material and personnel dependence, which fundamentally affects its ability to respond to crisis situations. Modern production of weapons and ammunition relies on specific raw materials, rare metals, and components whose availability is limited in the European context. One of the most critical factors is the dependence on imports of rare-earth elements and special metals, which are essential for the production of electronics, sensors, propulsion systems, and precision-guided munitions. A large proportion of these raw materials comes from China, which has built up a near-monopoly position in their extraction and processing over the last two decades. This reality represents a geopolitical risk, as in the event of an escalation of tensions between the West and Beijing, supply disruptions could occur, which would paralyse not only the civilian but also the defence sector (Hackett et al., 2025).

The problem of a lack of a skilled workforce adds to the raw material dependence. After decades of stagnation and gradual decline in the defence industry, many companies found themselves without a sufficient number of experts capable of working with highly specialised technologies. At the same time, generational replacement in the sector is proving to be challenging—young professionals are often motivated to enter more promising sectors such as information technology, energy, or the civilian aerospace industry. The defence sector therefore faces a dual challenge: not only to retain existing know-how but also to attract a new generation of engineers, technicians, and scientists (Gould & Losey, 2022; Soler, 2025).

These dependencies weaken the EU's ability to achieve its declared strategic autonomy. Without a systematic solution to the issue of necessary raw materials—for example, through the diversification of imports, recycling programmes, or investment in domestic sources—and without investments in education and professional training in the defence sector, the European defence industry will remain vulnerable to external shocks.

When evaluating the barriers to European defence industrial integration, it is essential to compare it with other major military-industrial complexes, particularly those of the United States and Russia. These two powers represent contrasting models—the American model based on massive investment and technological innovation, and the Russian model built on the centralised mobilisation of resources for war.

The United States has by far the largest and most advanced defence industry in the world. The Pentagon's budget exceeds $800 billion annually, which is more than double the combined defence spending of EU Member States (SIPRI, 2025). This volume allows American companies to plan long-term investments and maintain extensive production capacities that can quickly adapt to changes in demand. Moreover, the high concentration of the industry into a few giant corporations (Lockheed Martin, Boeing, Northrop Grumman, Raytheon) reduces fragmentation and allows them to achieve economies of scale that are currently completely unattainable in the European context.

In the US, there is also a strong link between the civilian technology sector and the defence sector. Venture capital, which typically avoids defence projects in Europe, is a key source for innovation development in the US. The result is an ability to quickly transfer breakthrough technologies—for example, in artificial intelligence or space systems—from the civilian to the military sector (Kurç, & Neuman, 2017; Sezal & Giumelli, 2022).

Russia, on the other hand, represents a model of a strongly centralised and state-controlled defence industry. Although its financial resources are limited compared to the West, its ability to focus all available capacities on the war effort ensures short-term resilience. The war in Ukraine has shown that the Russian industry can quickly mobilise a significant volume of production, especially in artillery ammunition and armoured vehicles, even if often at the expense of quality and technological sophistication. Russia currently operates in a "war economy" mode, in which civilian sectors are subordinated to the needs of the military. However, this model is unsustainable in the long run, as it leads to technological backwardness and economic stagnation (Cooper, 2025; Grisé et al., 2025).

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Compared to these two models, the EU faces a unique dilemma. Unlike the US, it does not have a single budget or a centralised acquisition policy, and unlike Russia, it cannot sacrifice its civilian economy for the sake of wartime mobilisation. The Union is therefore forced to seek a compromise between national interests and common EU goals, between public and private investment, and between technological ambitions and fiscal limitations. These differences show that while the EDIS and EDIP represent important steps towards European defence integration, their success will depend on the EU's ability to overcome structural barriers that have no parallel in either the American or the Russian model.

5. Perspectives and Opportunities: Building a Resilient, Sustainable, and Competitive European Defence Industry

Despite the numerous barriers and limitations that hinder the development of a common European defence industrial space, we cannot overlook the positive trends and new opportunities that have emerged in recent years. The EDIS and EDIP represent the EU's first comprehensive attempt to create a systemic framework that aims to shift the European defence industry from a reactive and fragmented model to a coherent and forward-looking industrial ecosystem.

One of the greatest opportunities is the increased political will of the Member States to strengthen the defence industry. The war in Ukraine has fundamentally changed political discussions about defence. A topic that was marginal in many countries for years has now become a top priority. While before 2022 it was not possible to reach a consensus on common funding or the coordination of defence industrial capacities, today the willingness to seek European solutions is much higher (Fiott, 2023). This shift creates a window of opportunity that would be a mistake to miss.

Another positive trend is the growing interoperability and integration of production chains. Joint projects funded by the EDF and pilot initiatives under the EDIS show that European companies are capable of collaborating and jointly developing products that have potential not only for the European but also for the global market. If this trend can be solidified, Europe can significantly reduce its dependence on American and other suppliers while simultaneously increasing its export capacity.

Positive signals are also coming from the innovation ecosystem. Universities, technology centres, and startups increasingly view the defence sector as a legitimate area of their activities. Cooperation between civilian and military research, particularly in the field of dual-use technologies, creates the preconditions for the emergence of breakthrough innovations. If the stigma associated with investing in defence can be removed, Europe could leverage its rich innovation potential to strengthen its own defence while also creating new economic opportunities (Kotila et al., 2023).

Lastly, the EU's effort to forge strategic partnerships with third countries can be seen as a promising perspective, as it can reduce raw material and technological dependence. Initiatives to diversify the supply of rare metals, cooperation with Canada, Australia, and African partners, and the strengthening of transatlantic ties in industrial cooperation represent a way to minimise the risks arising from a one-sided dependence on China or other authoritarian regimes (European Commission, 2021; Grüning, 2023).

The economic dimension is a key prerequisite for the success of European defence industrial integration. While funding was previously seen primarily as a limiting factor, new possibilities are now emerging that could fundamentally change the investment framework for this sector. One of the most significant opportunities is the potential to create European investment schemes for defence, modelled on the successful NextGenerationEU instrument launched during the pandemic. Such an approach would make it possible to mobilise resources at the Union level, thereby eliminating the asymmetry between Member States with high fiscal capacity and those that lack the funds for large-scale modernisation programmes. Common European loans or Eurobonds for defence could create a stable, long-term financial foundation for the implementation of the EDIS (Dermine, 2025).

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A crucial element in building a resilient and competitive European defence industry will also be the ability to keep pace with technological development while creating its own breakthrough innovations. If the EU succeeds in establishing itself as a technological leader in defence, it will gain not only military capabilities but also broader economic and geopolitical influence. One of the most significant areas is artificial intelligence (AI) and its applications in the defence sector. AI is increasingly used for processing intelligence data, autonomous systems, and real-time command of combat operations (Csernatoni & Mavrona, 2022). Europe has a strong academic and research base in this area, but it cannot yet compete with the investment dynamism of the US or China. Programmes funded by the EDF and EDIS can create a platform for coordinated European projects that bring together universities, research institutions, and industrial companies (Fiott, 2023).

The field of cyber defence is equally promising, having become an integral part of security strategies in recent years. With the increasing number of cyberattacks, including those that are part of the hybrid war against Ukraine, cyber resilience is becoming crucial for military as well as civilian infrastructures. European companies and research centres possess high expertise in cryptography, security software, and network security, which represents an area where the EU can achieve a comparative advantage (Csernatoni & Mavrona, 2022; Martino & Gamal, 2022; Andrassy & Ondrus, 2024).

Another opportunity is the development of space capabilities. Satellite communication, Earth observation, and navigation systems are an essential element of modern military operations. The EU already operates systems like Galileo and Copernicus, which are of strategic importance, but their full potential for the defence industry has not yet been fully exploited. Integrating these programmes with the EDIS could strengthen European autonomy in the space domain and reduce dependence on the US (Centrone & Fernandes, 2024).

A further essential prerequisite for building a resilient and competitive European defence industry is overcoming national protectionism and strengthening trust among Member States. Past experience shows that many ambitious projects have failed precisely because of differing national priorities and disputes over industrial shares in contracts. If the European defence industry is to be truly integrated, it will be necessary to create fair mechanisms for distributing production and know-how that both respect legitimate national interests and promote supranational, Union-wide efficiency, effectiveness, and purpose (Mueller, 2024).

In the context of all the above, we must not forget other fundamental challenges, as well as opportunities, related to the green, energy, and digital transformations. If the EU succeeds in integrating energy, environmental, and digital criteria into the defence industry without them being perceived as a drag on investment, it can become a leader in "green defence." Energy efficiency, the use of renewable energy sources, new propulsion systems, and the digitalisation of production processes can create a new standard that would allow Europe to establish itself on the global market (Kavan et al., 2021; Vincorion, 2024; Tvaronavičienė, 2024; Tavares da Costa et al., 2023; Dirma et al., 2024; Okunevičiūtė et al., 2025; Dušek, 2025).

The long-term perspectives thus show that the European defence industry can become one of the pillars of European economic and security power. Success, however, will depend on the ability to combine resources, innovation, and political will within a supranational framework. If the EU can harmonise these factors, tackle the difficult challenges, and overcome existing barriers, it can build a resilient industrial defence ecosystem that will not just be a reaction to the current crisis but also a long-term strategic asset in a new geopolitical era.

Conclusions

In the introduction to this article, we asked how the European Union, through its new defence industrial strategy—represented by documents such as the EDIS and EDIP—is addressing the challenges of fragmentation, funding, and competitiveness within its defence industry in a new geopolitical era. The analysis has shown that the return of war to Europe has fundamentally affected not only the security but also the political and economic environment in which the European defence industry operates. What was once a marginal area has become a strategic priority, essential for the security and defence, as well as the economic stability, of the European Union.

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The geopolitical framework highlighted that the war in Ukraine and uncertainty regarding future US involvement in European security have accelerated discussions about strategic autonomy. This concept is gradually transforming from a primarily political ambition into an economic and industrial concept that emphasises production capacity, investment attractiveness, and technological sovereignty.

Within the analysis of the European defence industrial strategy, we identified three main pillars: strengthening the internal market, supporting innovation, and increasing the share of European funding. The quantitative targets, such as achieving 50–60% of procurement from within the EU and 40% collaborative procurement, represent ambitious yet realistic milestones. If these goals are met, Europe can reduce its external dependence and create a robust market that will support the competitiveness of its industry.

Despite these ambitions, limitations and barriers persist that threaten the rapid implementation of the strategy. These include, in particular, ongoing national protectionism, a lack of production capacity, low investment attractiveness caused by the ESG framework, and raw material and personnel dependencies. The comparison with the US and Russia showed that the Union faces structural disadvantages—it has neither the centralised power of the United States nor the mobilising character of Russia's "war economy." It must therefore find its own model that combines economic efficiency with respect for political and institutional diversity.

On the other hand, there are also perspectives and opportunities on the horizon that could move the European defence industry into a new phase of development. Increased political will, common European funds, reforms to the investment framework, and groundbreaking technological innovations—from artificial intelligence and cyber defence to space capabilities—form the foundation upon which a resilient and competitive industrial ecosystem can be gradually built.

Based on the analysis performed, several recommendations for the future can be formulated. First, it is necessary to systematically anchor the funding of defence industrial integration into the long-term EU budgetary framework. This would prevent a situation where investments are made only in reaction to crises and would create stability for the planning of production and research projects.

Furthermore, it is essential to re-evaluate ESG regulations to reflect the specific needs of defence. Defence should be recognised as a prerequisite for sustainable development—without security, it is impossible to ensure either environmental or social goals. This would allow the sector to be opened up to a wider range of investors, including institutional and private capital.

Strengthening education and human resource development also plays an irreplaceable role. The Union should invest in technical and engineering education and foster the connection between civilian and military research programmes. This would ensure the continuity of know-how and attract a new generation of experts, without whom it is absolutely impossible to maintain technological competitiveness.

Another priority is the support for dual-use technologies and the green transition. Investments in defence would thus become more socially acceptable, as they would also bring direct benefits to civilian sectors—from energy efficiency to digital infrastructure. Finally, it is important to develop strategic partnerships with third countries that can provide access to raw materials and technologies that the EU does not have itself. Cooperation with Canada, Australia, South Korea, or countries in Africa can contribute to the diversification of supply chains and strengthen resilience to geopolitical shocks.

If these recommendations can be implemented, the European Union will be able to transform the current security and industrial crisis into a long-term opportunity. The defence industry could become not only a pillar of security and defence policy but also one of the foundations of economic growth, technological modernisation, and Europe's strategic autonomy in a new geopolitical era.

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THE ASSESSMENT OF RELATIONSHIP BETWEEN HUMAN CAPITAL AND ECONOMIC PERFORMANCE IN SLOVAKIA, POLAND AND SWEDEN*

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Abstract. The role of human capital as an important driver of economic and social development is well-established. Economic theory, and even more so economic practice, seeks to assess its impact on labor productivity and economic growth. The goal of this paper is to design and construct a human capital index comprising pertinent indicators, use it to evaluate human capital in selected European Union countries (Slovakia, Poland and Sweden), and then to identify the relationship between human capital and economic growth in the three countries. Unlike the HCI compiled by the World Bank, which focuses primarily on outcome indicators and evaluates more than 170 different countries, our proposed index also includes cost indicators. This index is designed for developed countries, where indicators such as the under-five mortality rate or expected length of schooling up to a certain age are less meaningful. The analysis was conducted for the period spanning 2014 to 2023 using statistical country data from Eurostat. Descriptive statistics, one-factor analysis of variance, Tukey HSD test, base index, geometric mean, correlation, regression, and comparative analysis were employed to fulfill the objectives of the paper. The Human Capital Index (HCI) showed the lowest value at the beginning of the observed period in Poland. However, in the subsequent years, Poland exhibited a more pronounced trajectory of human capital, as evidenced by its surpassing Slovakia in terms of HCI growth. In Sweden, the human capital index in 2014-2023 was significantly higher than in Slovakia and Poland. The GDP growth rate exceeded the average growth rate of the human capital index in all three countries, i.e. in all countries economic growth outpaced human capital growth, but the differences in favor of economic growth were modest. Nevertheless, it can be reasonably assumed that the differences in favor of economic growth would have been more pronounced if economic development had not been slowed down by the Covid-19 outbreak.

Keywords: economic performance; HDI; human capital; human capital indicators; investment

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1. Introduction

The concept of human capital was introduced into economic theory by Becker, who defined this category in his seminal work, Human Capital (1964), and emphasized the importance of investment in human capital (Becker, 1964). In his other works he emphasized the impact of human capital development, education and training on income and economic growth. He argued that that all countries which have managed persistent growth in income have also had large increases in the education and training of their labor forces (Becker, 1994).

Human capital is of interest to both developing and developed countries, as it is the basis for both economic and social progress. Particular focus has been on its impact on the economic performance of individual countries. It has already been established that human capital can become an important factor in economic growth, especially for small economies that lack natural resources. However, the development of knowledge economy processes and emergence of the Industry 4.0 concept, its value has increased in all countries. The knowledge economy, along with the technological revolution, is precipitating fundamental changes in labor markets. In the modern era, employment is increasingly dependent on individuals possessing specific knowledge, skills, and critical or abstract thinking abilities. This places greater emphasis on the development of human capital. The utilisation of specific knowledge and skills, as well as critical or abstract thinking, in the workplace is becoming increasingly prevalent, thereby placing greater demands on the elevation of human capital. While developed countries are engaged in systematic efforts to enhance their human capital, the majority of research on this topic originates from developing countries. While the economic performance of countries can be readily quantified in terms of macroeconomic indicators, the assessment of human capital is more challenging due to its qualitative nature. In light of these considerations, international organizations are increasingly proposing alternative indicators for the assessment of human capital and for the ranking of countries. This is because the interdependence between human capital and economic growth is easier to demonstrate in developing countries. While economic performance is relatively easy to be expressed through macroeconomic aggregate indicators, the process is more complex for human capital as it is a qualitative variable. For this reason, international institutions are increasingly proposing various indicators by which human capital can be assessed or quantified and are issuing rankings that include countries across the world. At present, the most comprehensive indicator of human capital levels is the Human Capital Index (HCI), as reported by the World Bank. The HCI quantifies the potential for human capital accumulation in adulthood, taking into account the risks associated with health conditions and inadequate levels of education (World Bank, 2018). The index assesses the level of human capital in more than 170 countries around the world. The same methodological approach is applied in each of the countries included in the analysis, thereby avoiding the potential for significant differences between them to have an impact on the findings. However, not all indicators through which the level of human capital in developing countries is expressed can be used in the conditions of developed countries, as diametrically different initial conditions need to be considered. However, the indicators utilized for developing countries are frequently not applicable to developed countries, including those within the European Union. Moreover, although human capital in developed countries, including EU countries, is frequently quantified through a multitude of sub-indicators, the lack of a more comprehensive indicator that encompasses the level of human capital in these countries offers significant opportunities for research, particularly in the development of novel indicators and the examination of their correlation with economic growth. both in terms of constructing the indicator and, subsequently, in terms of examining the relationship between the level of human capital in a society and the economic situation of a country.

The objective of this paper is to design and construct a human capital index comprising pertinent indicators, utilize it to evaluate human capital in selected European Union countries (Slovakia, Poland, and Sweden), and subsequently identify the correlation between human capital and economic growth in these three countries. To achieve the stated objective, a number of scientific methods were employed, including time series analysis (base index, geometric mean) and correlation and regression analysis. The latter was used to evaluate the relationships between the variables under study. These methods were complemented by the one-factor analysis of variance and by the method of comparison, which provides a useful framework for comparing different data sets in order to identify differences or similarities in their evolution.

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The literature review identifies the theoretical approaches that have been proposed to address the issue, identifies the key determinants that influence the level of human capital, and summarizes the findings of previous research in the observed area. In the methodology section, the construction of the human capital index was discussed in greater detail. Furthermore, additional methods employed during the preparation of this document are discussed, including correlation and regression analysis, one-factor analysis of variance, Tukey HSD test, as well as the calculation of the geometric mean. In the Results section, the differences between Poland, Slovakia, and Sweden, as identified through the chosen analyses, are compared. Through discussion, our findings were compared with those of other authors who have dealt with the same or similar issues. In the final part of the paper, in addition to a summary of the research findings, the limitations of the study and suggestions for further research in this area were also presented.

2. Theoretical background

Economic growth in modern societies is driven by innovations, with highly skilled professionals acting as the primary generators (Gruzina et al., 2021; Ahmed, Piccinetti & Rezk, 2024; Laužikas et al., 2025). This is a reality for the majority of countries in the 21st century, which has led to a growing focus on human capital. Some economies with abundant mineral wealth have historically placed a significant emphasis on natural resources. However, in light of global developments, they are beginning to recognize the necessity of prioritizing the advancement of human capital to ensure long-term economic sustainability (Aljarallah, Angus, 2020). However, despite these global trends, the situation in some countries does not indicate that they have implemented substantial changes in their approach to human capital. This also applies to the Slovak economy, which is relatively undercapitalized in terms of human capital, lagging behind the most advanced EU countries. Furthermore, this issue is exacerbated by the emigration of skilled individuals with knowledge to higher-income countries such as Germany, Austria, and, more recently, the Czech Republic (Palaščáková et al., 2019; Steyn & Ndofirepi, 2024).

While economic growth can be relatively easily expressed through macroeconomic aggregate indicators, even these are sometimes a subject to criticism (Gonos et al., 2022), the level of human capital development is more complicated to express. One issue arises from the fact that there is no consensus on the definition of human capital. A further issue is that human capital is a qualitative attribute of human beings. In order to facilitate its use in relation to economic indicators, it must therefore be expressed quantitatively. Furthermore, it is important to acknowledge that human capital exerts a more pronounced influence on economic growth over the long term, as opposed to its impact in the immediate future (Rahman et al., 2023).

The Organisation for Economic Cooperation and Development (OECD, 2007) defines human capital as a set of human capabilities that are formed by upbringing and education and shaped by the health situation of the individual in question. A substantial body of research (e.g., Tahsin, 2019; Balsmeier & Woerter, 2019; Ershova et al., 2019; Wolf, 2020) has examined the relationship between human capital and economic growth, particularly within the context of education. This is because education is widely regarded as a fundamental prerequisite for the development of human capital. According to Boachie and Adu-Darko (2024), supporting human capital development through improving its unique skills and competencies can lead to a more significant improvement in economic growth. Dore and Teixeira (2023) have demonstrated that formal education is a critical factor in promoting economic growth. The same fact is also pointed out by Simmons (2024), according to whom education plays a significant role in increasing the level of human capital and creating innovations, which subsequently translates into the economic prosperity of the country. Other authors, such as Madsen (2012), contend that health is of greater consequence than education. The state of health has a significant influence on the quantity and quality of learning, innovation, and growth. Health affects the capacity to learn, to think, and to introduce novel concepts. Consequently, the importance of healthy human capital for economic growth outstrips that of educational attainment. Gulcemal (2020) also addressed the health of human capital, establishing a correlation between it and life expectancy. He concluded that extending life expectancy has positive economic consequences. As life expectancy rises, the workforce is likely to remain employed for longer periods, which should help to reduce the financial burden of pension expenditure and improve the health of the elderly. Railaite and Čiutienė (2020) established a correlation between the growth in life expectancy and the level of expenditure allocated to the healthcare sector. The importance of health spending is also confirmed by

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Magida et al. (2025), who find that government spending on health significantly improves human capital development, but its impact varies depending on the level of economic development of countries, with government spending having a greater impact on human capital in more developed countries. In addition to the aforementioned authors, numerous other scholars have emphasized the importance of investing in specific areas that directly influence human capital levels. Nezhnikova (2020) posits that investment in human capital represents a fundamental driver of future economic progress at the national level. She specifically highlights the necessity of allocating resources towards three key domains that are integral to its advancement: investment in education, healthcare, and science and research. Similarly, Di Cataldo and Rodríguez-Pose (2017) establish a connection between human capital and investment in a range of areas beyond education. However, Bedianashvili et al. (2024) point out in this regard that increased spending on human capital may not be immediately reflected in economic growth rates due to long-term effects and structural inefficiencies.

In their 2016 study, Laskowska and Danska-Borsiak emphasized the necessity of considering the three phases of the human capital life cycle—creation, maintenance, and utilization—in order to gain a comprehensive understanding of the relationship between human capital and economic performance across EU countries. The formation of human capital must take into account not only the reproductive capacity of the population but also the accessibility of healthcare and education. The maintenance of human capital, as well as its creation, is contingent upon access to healthcare and also to lifelong learning and culture. The utilization of human capital is reflected, for instance, in the documented rate of employment (proportion of employment in sectors other than agriculture, employment in knowledge- and technology-intensive sectors, etc.) or unemployment. Moreover, the capacity for innovation and involvement in research activities in countries can be observed in terms of human capital utilization. As Leite and Cardoso (2023) posit, the advancement of R&D and engagement in research activities are similarly crucial, as R&D fosters innovative capacity creation, which in turn enhances the overall economic structure. Similarly, Ivanová and Čepel (2018) emphasize the necessity for countries to enhance their innovation performance. These factors are regarded as instrumental in the prosperity of developed economies. Garbuz and Topala (2017) highlight the necessity for consistent investment in research and the training of professionals in this field in order to address the aforementioned issue. as the main source of sustainable economy development.

In the context of the ongoing pandemic, numerous studies have commenced investigations into the influence of human capital on economic performance, as evidenced by the works of Dvorak et al. (2020), Ismayilzade et al. (2021), and Sun et al. (2022). In a study published in 2023, Chaabouni and Mbarek examined the relationship between human capital and economic growth in the Euro Area before and after the onset of the pandemic. Their findings indicated that prior to the crisis, investments in education and health had a positive impact on economic growth., After the pandemic, however, this positive effect ceased. In their study conducted in Azerbaijan, Ismayilzade et al. (2021) found that during the ongoing pandemic and subsequent crisis, the qualitative characteristics of human capital have a greater impact on economic development than the quantitative characteristics typically used in research. However, the authors contend that these findings cannot be evaluated over the long term, as they only observed the short-term impact of human capital on a country's economic development. Nevertheless, this correlation is more distinctive in the long run (Rahman et al., 2023). Furthermore, in the context of social isolation during the pandemic, there has been a notable shift in focus towards digitization processes in economies. In light of these considerations, other authors (Osipov et al., 2021; Chernenko et al., 2021; Medennikov et al., 2021) have underscored the significance of digitization development in economies and have examined its impact on the demands placed on the quality of human capital.

The majority of studies examining the relationship between human capital and economic growth address the interdependence between the two. Jaghoubi & Alfalih (2025) state that there is a bidirectional causal relationship between GDP development and human capital development. However, Wang et al. (2022) argue that despite the existence of relevant findings in this area, it is essential not to prioritize the examination of the causal relationship between the variables under investigation. Instead, the emphasis should be on research examining the factors influencing the interrelationship and coordination of these variables. Only when these variables are congruent and mutually supportive will this result in mutually beneficial development outcomes.

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As evidenced by the literature review, human capital can be expressed through a variety of sub-indicators. However, as previously indicated in the introduction, a more comprehensive indicator is lacking in developed countries, including those in the EU, that could effectively express the level of this capital. This fact prompts us to attempt to construct a human capital index appropriate for the circumstances of European countries in the empirical section of this study, based on the aforementioned background. This will then become the subject of further analyses examining the correlation between the level of human capital and the rate of economic growth in the selected three countries (Slovakia, Poland, Sweden).

3. Research objective and methodology

The objective of this study is to develop a human capital index comprising relevant indicators, utilize it to assess human capital in selected European Union countries (Slovakia, Poland, and Sweden), and subsequently identify the relationship between human capital and economic growth in the three countries. The countries of Poland and Slovakia were selected for comparison due to their geographical proximity and shared membership in the Central European region, as well as their similarities in socioeconomic conditions. In order to highlight the differences between developed and less developed countries, Sweden, which is one of the most developed countries in the EU, was included in the comparison. The analysis was conducted using statistical data from Eurostat for the period between 2014 and 2023. The analysis is constrained to the period between 2014 and 2023 due to the unavailability of essential indicators required for the computation of the human capital index. While some of the indicators are also available for the year 2024, the Healthy Life Years indicator is not, having last been updated in Jule 2025 with a two-year lag and a validity period of 2023. Similarly, the indicator on the share of professionals in research and development (R&D) is only available until 2023. Accordingly, in order to ensure the consistency and compatibility of the data throughout the analysis, it was not feasible to utilize more recent data.

Firstly, we designed and calculated a Human capital index. In the index calculations we included six indicators from three areas: education, health, and R&D, through which it was possible to capture human capital in 3 stages of its life cycle (Laskowska & Danska-Borsiak, 2016). Thus, the following sub-indicators were part of the index calculations:

1. the evolution of population share aged 15-64 with tertiary education
2. per capita public expenditure on education
3. Healthy Life Years in absolute value at birth
4. per capita public expenditure on health
5. per capita expenditure on research and development
6. share of R&D workers in the total active population.

Hence, we included both outcome and cost indicators in the index (Kwon, 2009), all of which were first recalculated by a base index relative to the European Union average in 2014, set as the base year. In the next step, the reported values of the base index were converted into points as follows: the base index value reached 0 % to 20 % → 0.1 point assigned; 21 % to 40 % → 0.2 point; 41 % to 60 % → 0.3 point; 61 % to 80 % → 0.4 point; 81 % to 100 % → 0.5 point; 101 % to 120 % → 0.6 point; 121 % to 140 % → 0.7 point; 141 % to 160 % → 0.8 point; 161 % to 180 % → 0.9 point; 181 % and more → 1 point. The scores were then incorporated into the formula for the index, which was subsequently multiplied by the weights assigned to each indicator. As the theoretical studies conducted by other authors have primarily focused on the significance of individual indicators, without providing a precise assessment of their impact on human capital development, we have elected to assign equal weight to each of the included indicators.

1. population share with tertiary education: weight assigned 16.66%
2. public expenditure on education: weight assigned 16.66%
3. Healthy Life Years at birth: weight assigned 16.66%
4. public expenditure on health: weight assigned 16.66%
5. research and development expenditure: weight assigned 16.66%.
6. share of R&D workers in the total active population 16.66%.

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Formula: AHCI = 0.1666 . AVI1 + 0.1666 . AVI2 + 0.1666 . AVI3 + 0.1666 . AVI4 + 0.1666 . AVI5 + 0.1666 . AVI6, where:

AHCI - actual human capital index
AVI1 - achieved value for indicator 1 (population share with tertiary education)
AVI2 - achieved value for indicator 2 (public expenditure on education per capita)
AVI3 - achieved value for indicator 3 (healthy life years in absolute value at birth)
AVI4 - achieved value for indicator 4 (public expenditure on health per capita)
AVI5 - achieved value for indicator 5 (research and development expenditure per capita).
AVI6 - achieved value for indicator 6 (share of R&D workers in the total active population).

Following the creation and calculation of the index values for the observed countries, we proceeded to the subsequent phase of the research. The correlation analysis method was used to determine the degree of dependence between the level of human capital and economic growth in Poland, Sweden and Slovakia. The dependent and independent variables were defined as GDP per capita and the value of the index of human capital created. The Pearson correlation coefficient was used in the calculations:

$$r_{xy} = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{\left[n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2\right]\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2\right]}}$$

Furthermore, a significance test of the correlation coefficient was conducted to ascertain whether the observed dependence is statistically significant in the observed countries. This would indicate whether the results can be generalized to the entire base population. The following formula was used in the calculations:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$$

To identify differences between the countries studied in the area of human capital, we applied the one-way analysis of variance (ANOVA) method. To refine the results and determine statistically significant differences between individual pairs of countries, the one-way analysis of variance was supplemented with the Tukey HSD test. We based our calculations on the formula:

$$HSD = q_{crit} * \sqrt{\frac{MS_{within}}{n_{ef}}}$$

For the regression calculations, it was necessary to find the data (regression coefficient b_1 and constant b_0) necessary to be put into the linear regression function: $y = b_0 + b_1 x + \mathcal{E}$.

By means of the geometric mean $x_G = \sqrt[n]{x_1 . x_2 . \ldots x_n}$ we calculated the average growth coefficient of Human capital index and the average growth coefficient of GDP to figure out whether in observed countries the human capital growth exceeds the economic growth or vice versa.

4. Results

In accordance with the methodology outlined in the preceding section, we have calculated a human capital index for Poland, Slovakia, and Sweden based on the six sub-indicators (share of population with tertiary education, public expenditure on education, healthy life years at birth, public expenditure on health, expenditure on research and development, and share of R&D workers in the total active population) using the aforementioned procedure (see Table 1). The individual sub-indicators included in the index calculation were evaluated in comparison to the EU average for 2014. In comparison to the EU average, Sweden demonstrated superior

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performance across all indicators. This was not the case for Slovakia and Poland. This discrepancy in the level of countries is also reflected in the reported index values.

Table 1. The Human Capital Index

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Poland	0.32	0.33	0.33	0.37	0.38	0.38	0.38	0.42	0.45	0.46
Slovakia	0.33	0.33	0.35	0.35	0.37	0.37	0.38	0.42	0.42	0.45
Sweden	0.83	0.83	0.85	0.85	0.85	0.85	0.86	0.91	0.91	0.91

Source: Eurostat, own calculating

As illustrated in Table 1, the Human Capital Index exhibited the lowest value at the outset of the observed period in Poland. Nevertheless, the country subsequently surpassed Slovakia. In Poland, however, the value of the index exhibited a more pronounced increase, although this country is slightly behind Slovakia in economic terms. The Human Capital Index for Sweden exhibited a markedly higher value than that observed in Slovakia or Poland during the 2014-2023 period. This is an unsurprising outcome, given that Sweden is one of the most advanced countries in the EU. The dynamics of development were highest in Poland, where the human capital index increased by 0.14 points in the period under review 2014-2023, followed by Slovakia with an increase of 0.12 points and Sweden with an increase of 0.8 points. As the subsequent section of the study will examine the relationship between the human capital index and economic performance in the selected countries, it is essential to provide a concise overview of their economic circumstances. In accordance with the majority of existing studies, we have employed gross domestic product as an indicator of economic performance (see Table 2).

Table 2. GDP in market prices per capita in €

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Poland	10 750	11 390	11 270	12 360	13 280	14 190	14 310	15 770	17 520	19 980
Slovakia	14 130	14 820	15 030	15 620	16 580	17 340	17 270	18 730	20 150	22 640
Sweden	44 930	46 160	46 790	47 210	45 770	46 110	46 180	51 260	51 980	50 490

Source: Eurostat

The economic situation in the observed countries was relatively favorable until 2019. In the majority of years, both Poland and Slovakia have demonstrated positive economic growth. However, in 2020, the world was struck by the global pandemic of the novel coronavirus, which disrupted the previously established stability. All three countries were affected by a decline in GDP. However, the economies demonstrated a rapid capacity to adapt to the new circumstances. In 2021, despite the persistence of the pandemic, economic growth was already being observed in these countries. However, in addition to the impact of the pandemic, the overall economic development in Sweden has exhibited some anomalies in comparison to the rest of the countries. In 2018, the country experienced a more pronounced economic deceleration than in the pandemic year of 2020. Following the identification of the development of human capital and GDP in the observed countries, further analyses could be conducted. Correlation and regression analyses were conducted for each country at the $\alpha = 0.05$ significance level.

Table 3. Testing statistics

	Poland	Slovakia	Sweden
Pearson correlation coefficient r	0.981	0.977	0.953
Correlation coefficient significance test	0.000	0.000	0.000
Determination coefficient r^2	0.962	0.954	0.908
Constant b_0 (p- value)	8394.8 (0.000)	-7509.7 (0.004)	-13 174 (0.090)
Regression coefficient b_1 (p-value)	58 870 (0.000)	65 947 (0.000)	70 372 (0.000)
$y = b_0 + b_1x$	y = -8394.8 + 58 870x	y = -7509.7 + 65 947x	y = - 13174 + 70 372x
F test p-value	0.000	0.001	0.000

Source: Eurostat, own calculating

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The correlation coefficient in Poland takes the value of 0.981, which indicates an almost perfect positive tightness of the relationship between the Human capital index and the level of GDP per capita. A significance test p-value of 0.000 < α (0.05) for the correlation coefficient indicates that the correlation coefficient is statistically significant, i.e. the result is not random. The determination coefficient (r^2) for Poland indicated that the selected model explained 96.2 % of the total variability, thereby confirming the appropriateness of the model selection. It may be posited that the elevated value of the correlation coefficient is attributable to the fact that both variables (human capital index and GDP) were undergoing considerable development in Poland.

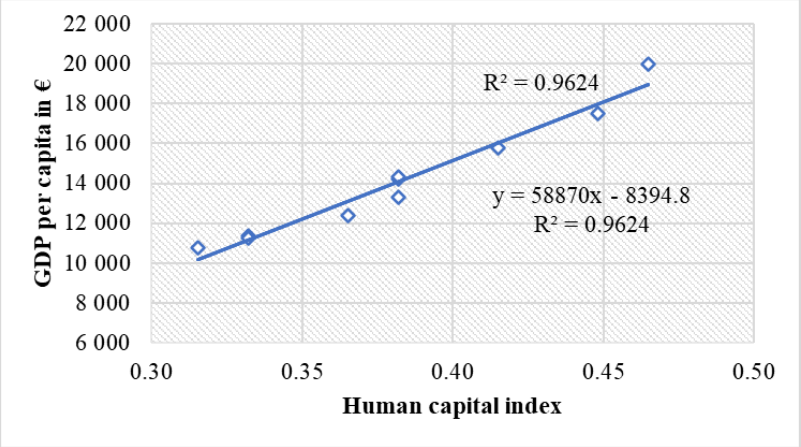


Figure 1. Correlation analysis – Poland
Source: Eurostat, own elaboration

The regression equation y = - 8 394.8 + 58 870x indicates that the function monotonic and increasing (see Figure 1), as evidenced by the positive value of the coefficient b1. Substitution of any value of the Human capital index for x would yield the GDP per capita in Poland that would have been achieved at a given value of the index. If the p-value for b0 is less than 0.05, this constant is statistically significant. Additionally, an F-test was conducted to assess the null hypothesis that the selected model is inadequate for explaining the observed relationship between the variables. The p-value of the F-test is 0.000 < α (0.05), indicating that the null hypothesis can be rejected, and the selected model is appropriate for explaining the observed relationship in the Polish context. In light of the calculated values of the sub-variables during the conducted correlation and regression analysis, it can be concluded that in Poland, there is an almost perfect positive dependence between the development of the Human Capital Index and the development of the GDP per capita level. The significant correlation between the variables indicates a proportional relationship in their development. In light of these considerations, it seems reasonable to posit that the expenditure indicators included in the index calculation are increasing in line with GDP growth, and that they contribute positively to the development of the outcome indicators. These include the growth of the population with tertiary education, the growth in the number of healthy life years, and the increase in the share of workers in research and development.

In Slovakia, the correlation coefficient value was 0.977 during the observed period, indicating a strong and statistically significant relationship between the human capital index and the GDP level per capita. The p-value of the significance test of the correlation coefficient 0.001 < α (0.05) indicates that in Slovakia as well as in Poland, there is a statistically significant dependence between the examined variables. It can be posited that this is due to the relatively dynamic development of both the human capital index and the GDP. Additionally, in the case of Slovakia, the suitability of the model was verified through the determination coefficient. This demonstrated that 95,3 % of the total variability was explained by the model, which can be considered sufficient.

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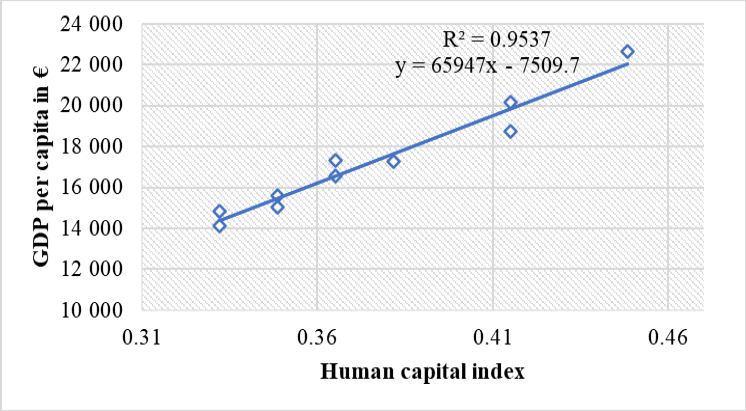


Figure 2. Correlation analysis – Slovak Republic
Source: Eurostat, own elaboration

The regression equation for the Slovak Republic has the form y = - 7509.7 + 65 947x, indicating a monotonic increasing function (see Figure 2), similar to that observed in Poland. Substitution of any value of the human capital index for x would yield the GDP per capita in Slovakia that would have been achieved at a given value of the index. This could be used, for example, in estimating future development. The p-value for the regression coefficient b1 is 0.000, which is less than the alpha value of 0.05, indicating that this coefficient is statistically significant. In the case of the constant b0, the p value is 0.000, so this constant is also statistically significant. The p value of the F-test 0.000 < α (0.05) indicated that the chosen model was appropriate, as was observed in the case of Poland. In conclusion, it can be stated that the development in Slovakia exhibits only minor deviations in comparison to the development in Poland. Furthermore, a significant positive correlation was observed between the development of the Human Capital Index and the development of GDP per capita in Slovakia.

The correlation analysis conducted in Sweden yielded results that were comparable to those observed in Poland and Slovakia. The correlation coefficient of 0.953 indicates a robust and statistically significant relationship between the human capital index and the level of GDP per capita. The p-value of the significance test of the correlation coefficient was 0.000, which is less than the alpha value of 0.05. This indicates that there is a statistically significant relationship between the evolution of the human capital index and the evolution of GDP per capita. These findings are consistent with expectations, given the proportional evolution of both variables in Sweden. In light of the aforementioned evidence, it can be posited that the expenditure variables incorporated into the calculation of the human capital index have increased in parallel with GDP growth. Such a development had a favorable impact on the value of the correlation coefficient. The coefficient of determination (r^2) indicates that the model was able to explain 90.8 % of the total variability, which is a sufficient value, as was the case for the other two observed countries.

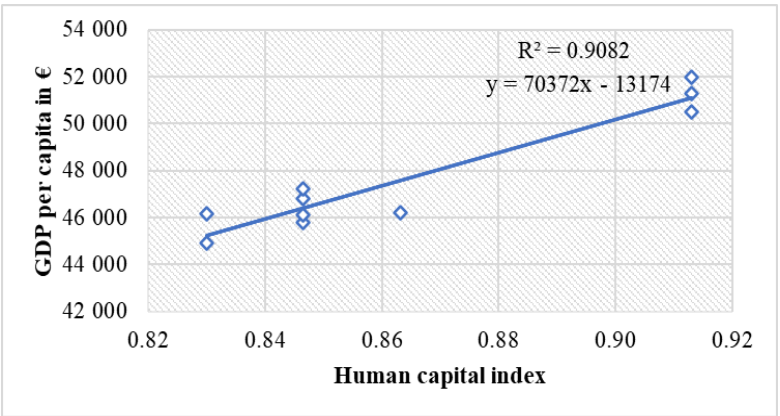


Figure 3. Correlation analysis – Sweden
Source: Eurostat, own elaboration

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From the regression equation y = -13 174 + 70 372x, it can be inferred that the function is monotonic and increasing (see Figure 3), a conclusion that is also supported by the data from the remaining two observed countries. Substitution of any value of the human capital index for x would yield the GDP per capita of Sweden at that value of the index. The p-value for the regression coefficient b1 was found to be less than α (0.05), indicating that this coefficient is statistically significant. However, in the case of the constant b0, the p-value was 0.090, which is greater than α (0.05), indicating that this constant is not statistically significant. Accordingly, the selected model is validated, and an F-test is performed. The null hypothesis was tested to ascertain the appropriateness of the selected model for explaining the relationship between the observed variables. The p-value of the F-test 0.000 < α (0.05) indicated that the null hypothesis could be rejected in the case of Sweden, as well as in the cases of Slovakia and Poland. This leads to the conclusion that the model used was indeed the appropriate one.

Although the correlation analysis did not reveal significant differences in the strength of the relationship between the variables studied, we decided to verify whether the HCI values differ statistically significantly between the countries. For this purpose, we used a one-factor analysis of variance (ANOVA), within which we formulated and tested the following hypotheses:
H0: There is no statistically significant difference in the average HCI value between the countries studied.
H1: There is a statistically significant difference in the average HCI value between the countries studied.

Table 4. One-factor analysis of variance

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Poland	10	3.82	0.382	0.0024
Slovakia	10	3.7534	0.37534	0.00157
Sweden	10	8.6456	0.86456	0.00116

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.57415	2	0.78707	460.451	1.37122E-21	3.35413
Within Groups	0.04615	27	0.00171			
Total	1.6203	29				

Source: Eurostat, own calculations

We performed the analysis at a significance level of α = 0.05. The calculated value of the test statistic F was 460.451, which was higher than the critical value F crit = 3.354. The p-value = 0.000 was extremely low. Based on such results, we have sufficient evidence to reject H0 that there is no statistically significant difference in the average HCI value between the countries studied. We accept the alternative hypothesis, which assumed that there are statistically significant differences in the average HCI value between the countries studied. In order to identify between which countries these differences are significant, we supplemented the one-way analysis of variance with the Tukey HSD test (see Table 5).

Table 5. Tukey HSD test

Groups	Difference	n1	n2	HSD	Significance
Sweden - Poland	0.483	10	10	0.05	yes
Sweden - Slovakia	0.489	10	10	0.05	yes
Poland - Slovakia	0.007	10	10	0.05	no

Source: Eurostat, own calculations

Tukey's HSD test was performed at a significance level of α = 0.05. The results indicate that the differences in the average HCI between Sweden and Poland, as well as between Sweden and Slovakia, are statistically

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significant. For the given pairs of countries, the calculated difference between their means was higher than the HSD = 0.05 value, which represents the minimum difference required to be statistically significant. On the contrary, the difference between Poland and Slovakia, which reached a value of 0.007, was lower than the specified HSD value. This difference was therefore not statistically significant, indicating that the average HCI value in these two countries is similar.

Additionally, some authors (Wang et al., 2022) have examined the discrepancy between the growth rate of human capital and the rate of economic growth. Furthermore, our objective was to ascertain the circumstances prevailing in the three countries under examination from the aforementioned perspective. A comparison of the growth rates of the human capital index and GDP was conducted using the average growth rate (see Table 6).

Table 6. Growth rate in % - the average growth rate of GDP and Human capital index (HCI)

	Poland		**Slovakia**		**Sweden**	
	GDP	**HCI**	**GDP**	**HCI**	**GDP**	**HCI**
2014	-	-	-	-	-	-
2015	106.0	105.3	104.9	100.0	102.7	100.0
2016	98.9	100.0	101.4	105.0	101.4	102.0
2017	109.7	110.0	103.9	100.0	100.9	100.0
2018	107.4	104.5	106.1	104.8	96.9	100.0
2019	106.9	100.0	104.6	100.0	100.7	100.0
2020	100.8	100.0	99.6	104.5	100.2	102.0
2021	110.2	108.7	108.5	108.7	111.0	105.8
2022	111.1	108.0	107.6	100.0	101.4	100.0
2023	114.0	103.7	112.4	108.0	97.1	100.0
Average growth coefficient	**1.071**	**1.044**	**1.054**	**1.034**	**1.013**	**1.011**

Source: Eurostat, own calculations

As illustrated in Table 6, the mean GDP growth rate exceeded the mean growth rate of the human capital index in all three observed countries. However, the discrepancies in favor of economic growth were relatively minor. In Poland, the value of the difference in average growth coefficients expressed as a geometric mean in favor of economic growth was 0.027, in Slovakia 0.02, and in Sweden 0.002. It seems reasonable to posit that the discrepancies in favor of economic growth would have been even more pronounced had there been no decline in GDP due to the pandemic crisis in each country in 2020. The correlation and regression analysis yielded no statistically significant differences between the observed countries. Moreover, the comparative analysis of average GDP growth rates and the human capital index did not yield any statistically significant discrepancies between countries at different stages of development. Irrespective of the economic performance and the level of human capital in the observed countries, the GDP growth rate was slightly higher than the growth rate of the human capital index in these countries. This indicates that the result is not influenced by the extent of the interdependence between the variables of interest or the socio-economic level of the countries in question. Therefore, further research is required to identify the relevant factors that may be influencing this relationship. This provides an opportunity for further investigation into this issue, with a view to identifying other factors that may influence the relationship between these two indicators, including the significant impact of artificial intelligence.

5. Discussion

The conducted analysis has demonstrated that countries typically attain both elevated economic levels and augmented levels of human capital (as exemplified by Sweden), whereas conversely, they often exhibit diminished economic levels and diminished levels of human capital (as evidenced by Slovakia and Poland). It has been demonstrated that Slovakia exhibits a lower level of human capital than the most advanced EU countries (Palaščáková et al., 2019). In comparison to Poland, however, Slovakia exhibits a relatively minor deficit. In light of the limitations of the World Bank's human capital index (HCI) in accurately reflecting the

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specific circumstances of European countries, our own index has been developed to address this gap. Additionally, the President of the World Bank has cautioned about potential deficiencies (World Bank, 2019). Our index incorporates cost and outcome variables. While some scholars (Kwon, 2009) have advised incorporating revenue indicators, we did not prioritize this due to the prevalence of cost indicators in existing studies (Nezhnikova, 2020; Linhartova, 2020; Di Cataldo, Rodríguez-Pose, 2017; Leite & Cardoso, 2023) or outcome indicators (Storesletten & Zilibotti, 2000; Tahsin, 2019; Madsen, 2016). The requisite indicators for calculating the human capital index were derived from three domains: education, health, and research and development. The significance of evaluating human capital, particularly through the use of indicators that reflect educational and health status, has been emphasized by Turganbayev (2023), for instance. In conducting the correlation analysis, the gross domestic product (GDP) was designated as the dependent variable. Accordingly, we employed a methodology analogous to that utilized by Alam (2023), who discovered that the human capital index and GDP exhibit a correlation precisely when GDP is employed as the dependent variable. The correlation between the level of human capital development and the economic growth rate was statistically significant in the countries under study. However, the Human Development Index was employed as a proxy for the level of human capital in the study. The significance test of the correlation coefficient revealed that the observed relationship is statistically significant in all three countries under consideration. In all three observed countries, human capital growth was slower than economic growth, which is at odds with the findings of Wang et al. (2022). In their study, the authors identified regions where human capital growth exceeded economic growth. However, some studies have demonstrated that increasing the level of human capital can promote economic growth (Tahsin, 2019; Diebolt & Hippe, 2019, among others). Consequently, it could be argued that enhancing and fostering human capital growth in a country is beneficial for its future economic and social development. These studies have demonstrated that even a relatively modest expansion of human capital can result in a significant enhancement of economic growth (Boztosun et al., 2016). This may provide an explanation for our findings that, irrespective of economic development, the growth of GDP has exceeded the growth of human capital in the observed countries.

Conclusions

The objective of this study was to develop a human capital index comprising pertinent indicators, utilize it to evaluate human capital in select European Union countries (Slovakia, Poland, and Sweden), and subsequently ascertain the correlation between human capital and economic growth in these three countries.

When creating the index, we drew on existing approaches to measuring human capital, but with the aim of adapting them to the conditions of developed countries. Unlike existing summary indicators of human capital, such as the HCI compiled by the World Bank, which assesses more than 170 countries worldwide from the least to the most developed, our proposed own actual human capital index (AHCI) focuses exclusively on European Union countries. Another difference is that while the HCI compiled by the World Bank focuses mainly on outcome indicators, our index also includes cost indicators, providing a more comprehensive view of the state and development of human capital, as it can be assumed that cost indicators create potential for the development of outcome indicators. The indicators assessed in the HCI (e.g., under-five mortality rate or expected years of schooling at age 18) may not be sufficiently informative for developed countries (the under-five mortality rate is low in developed countries and the expected length of schooling up to age 18 reaches its maximum limit, as most of the population in these countries completes secondary education). The novelty of the AHCI therefore lies precisely in its regional specialization and in taking into account indicators that are meaningful to evaluate in developed countries.

The results demonstrate that the country with the highest Human Capital Index value (Sweden) also exhibits superior economic performance. The results of the correlation analysis indicated a statistically significant relationship between the level of human capital development and economic growth. The results of the one-factor analysis of variance showed the existence of statistically significant differences in the mean HCI value between the analyzed countries. Subsequent post hoc analysis using Tukey's HSD test identified that statistically significant differences occur between Sweden and Poland and between Sweden and Slovakia.

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Another noteworthy observation is that, irrespective of the level of economic performance and human capital in the observed countries, GDP growth exhibited a slight excess over human capital growth in these countries. In light of the aforementioned results, it can be posited that this phenomenon is not contingent upon the degree of correlation between the observed variables or the socio-economic standing of the countries in question. It can be posited that this result is contingent upon additional factors that would necessitate future identification, as they may potentially influence future economic development in countries.

While the research has yielded insights into the relationship between economic performance and human capital development in Sweden, Poland, and Slovakia, it is important to acknowledge the limitations of the conducted research. To measure human capital, it is recommended that integrated indicators be used that are a combination of income, cost, and learning-based approaches. In addition, other aspects that determine the quality of human capital should be included (Kwon, 2009). However, the income aspect has not been considered, nor have other factors such as the level of democratization in each country or the level of poverty in each country. Furthermore, the research has not considered the impact of digitalization on human capital quality requirements, despite the growing recognition of this issue in recent years. Several studies have addressed this topic, including those by Osipov et al. (2021), Chernenko et al. (2021), Medennikov et al. (2021), and Zaborovskaia et al. (2020). Furthermore, the human capital index proposed here can be applied only when assessing the development of a country or countries in relation to a certain basic starting point. The index has been calculated in relation to the EU average for 2014, which may limit its use in other contexts or time periods, particularly in long-term comparisons.

The conducted research has yielded valuable insights into the relationship between human capital and economic growth in the three EU countries. The practical value of AHCI lies in the fact that it allows for better identification of the strengths and weaknesses of human capital development in individual countries, as it captures not only investments in human capital, but also their real effects, which should be reflected in performance indicators. However, it is also important to recognize the limitations of the research and the need for further extensions of the research to gain a more comprehensive understanding of the subject matter. The identification of additional factors or a correction of the methodology could contribute to a more comprehensive understanding of this issue and to more accurate predictions of future economic development in countries.

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RESEARCH ON THE STATUS AND POSSIBILITIES FOR DIGITIZATION OF WRITTEN CULTURAL AND HISTORICAL HERITAGE*

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Abstract. The digitization of written cultural and historical heritage is a key process for the preservation, access and promotion of the documentary memory of society. This study examines the status, challenges and prospects for the digitization of written cultural and historical heritage in Bulgaria. A survey was conducted among leading institutions in the field of management and preservation of written historical resources - libraries, museums, archives and others, to identify the main factors influencing digitization. The study was conducted from May to September 2025 and includes the opinions of 53 employees/experts in the field of written cultural and historical heritage. The aim of the study is to assess the status and opportunities for digitization of written cultural and historical heritage by identifying the main factors influencing successful digitization. From the analysis made, based on the data from the study, it can be concluded that at present the digitization of written historical resources in Bulgaria is at a relatively low level, caused by multiple factors. As a result of the analysis, it can be concluded that digitization is currently ineffective – limited access to digitized resources, incomplete digitized content, gaps in legislation, problems with ensuring copyright protection, etc. Based on the analyses performed, some recommendations have been made to improve the process of digitization of written cultural and historical heritage.

Keywords: digitalization; documents; archives; cultural and historical heritage

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1. Introduction

The digitization of written cultural and historical heritage is a key process in modern society, aimed at the preservation, accessibility and long-term preservation of historical memory. The development of modern information and communication technologies, including high-resolution scanning systems, optical character recognition (OCR), 3D modeling and cloud storage solutions, creates new opportunities for digital reproduction,

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cataloguing and analysis of archival documents, manuscripts and rare editions. At the same time, digitization is not only a technological, but also a cultural, organizational and ethical process that requires concerted efforts between institutions, specialists and legislators.

In the context of the growing digital transformation, written heritage is becoming a strategic resource for education, science and cultural identity. Digital collections and online archives expand public participation and provide new forms of interaction with cultural content through open access and shared platforms. However, the digitization process in Bulgarian institutions still faces several challenges related to insufficient funding, lack of standards and limited human resources. Researching these aspects is essential for the formulation of effective models and policies that will ensure the sustainable development of digital cultural and historical heritage in a national and international context.

This study attempts to reveal the opportunities for digitization of cultural and historical heritage in Bulgaria, considering the main factors and their manifestation. In this regard, the study seeks to answer the following questions:

RQ 1: What is the level and status of digitized written cultural and historical heritage in institutions in Bulgaria?
RQ 2: What factors influence the degree of digitization and what are the opportunities for using digitized written historical sources?
RQ 3: What are the opportunities for improving the process of digitization of written cultural and historical heritage and what would be the effects of digitization?

In response to the defined research questions, basic guidelines for developing effective models of digitization of written cultural and historical heritage can be revealed. On the other hand, this would also serve as a guideline for developing national and local policies, as well as updating the regulatory framework in the field of cultural and historical heritage in Bulgaria.

2. Literature review

There are numerous studies in the field of digitization of cultural and historical heritage in scientific literature (Nawaz et al., 2024; Lutfullayeva et al., 2025; Khatoon, 2025; Hadi et al., 2025). Different models and tools are used for the digitization of such resources. The main tool for digitization of archives and historical documents is information and communication technologies (ICT). Sabarrijan et al. (2024) examines the application of management information system (MIS) technologies to improve techniques for digital archiving and preservation of cultural heritage. The article outlines the problems that arise in relation to the maintenance and accessibility of historical documents and artifacts, focusing on digitization and data management.

Khan et al. (2018) examines the concept of digitization of cultural and historical heritage and opportunities for improving the management and dissemination of digitized historical resources. This study outlines the main challenges associated with initiatives for digital preservation of cultural heritage, including financial, technical, policy guidelines, legal aspects and metadata issues.

The main technology for digitizing cultural and historical heritage is 2D and 3D models. This technology creates new opportunities for the storage, distribution, research, documentation and analysis of cultural heritage. Three-dimensional digitization allows to produce a digital 3D model that can be virtually processed and recreated in any historical period, which allows for the preservation and protection of cultural heritage. Numerous publications are focused on this topic (Di Filippo et al., 2018; Milkova et al., 2019; García-Molina, 2021), as well as the development towards 4D (Bruno et al., 2022). Using 3D technologies, the main method for digitizing cultural and historical sources is scanning, which is used in various fields, even the digitization of clothing from historical

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periods (Montusiewicz et al., 2021). Recent research also highlights the managerial and technological aspects of digital transformation processes in Bulgarian organisations, emphasizing the importance of strategic alignment between digital transformation and corporate sustainability models (Koprinkova-Noncheva, & Dimitrov, 2022). The use of 3D technologies opens the opportunity to establish a workflow for digitization and management of cultural heritage that details staffing requirements, implementation processes, and quality control (Nguyen et al., 2022).

The construction of a 3D model is possible through modeling in Geographic Information Systems (GIS), which creates a suitable environment for remote sensing and preservation of cultural and historical heritage. Many authors (Trizio, Savini & Giannangeli, 2018; Pepe et al., 2021) have explored the possibilities of creating 3D-GIS models of tangible cultural and historical heritage, mainly buildings, but GIS can also be used in the digitization of written historical sources (archives, documents, books, etc.). In this way, GIS becomes a major tool for the digitization of cultural and historical heritage.

The effective digitization of cultural and historical heritage is dictated by the creation of a multimodal database – digital archives for various cultural heritage sites. The construction of a digital archive for data storage will help improve access and retrieval of digital assets of cultural and historical heritage for the necessary purposes (Batjargal, et al., 2023).

The digitization of written cultural and historical heritage aims to ensure sustainable access and preservation, but the specific nature and complex structure of written sources often make it difficult to apply conventional OCR (optical character recognition) technologies. Modern approaches based on advanced algorithms for segmentation, context recognition and machine learning offer effective solutions for the precise digitization and analysis of such archival sources.

The digitization of historical documents aims to provide easy access to archives for researchers and the public, which triggers citizen engagement in the management of cultural and historical heritage. The implementation of new technologies in the management of cultural and historical heritage gives rise to new forms of civic participation (Daga et al., 2022) and even new business models.

The advent of new technologies has also opened new opportunities for the digitization of cultural and historical heritage. Donghui et al. (2019) examine the possibilities of applying virtual reality technology in cultural heritage (Kassahun Bekele et al., 2018). Buragohain et al. (2024) explores the possibilities of applying the metaverse in the digitization of cultural heritage, covering various aspects of it to ensure sustainable accessibility to cultural resources. The effectiveness of the project for the digitalization of cultural and historical heritage is also determined by adhering to various constraints related to the management approaches used with IT teams. In this regard, it is necessary to apply the appropriate methodologies (Anguelov & Angelova, 2016).

Artificial intelligence (AI) has also prompted a new look at the management and accessibility of cultural and historical values. Sánchez-Martín et al. (2025) examine the impact of AI on the management, personalization of services, accessibility, and preservation of both tangible and intangible cultural heritage assets. In their study, the authors also highlight the main ethical, technical, and epistemological challenges associated with this transformation, including algorithmic surveillance, data protection, interoperability between platforms, and the reconfiguration of knowledge production processes for cultural heritage. Similar challenges in implementing AI are also observed in the service sector, where managers express hesitation, low trust, and the need for clearer regulation and organizational preparation (Dimcheva & Stoyanov, 2023).

The digitization of cultural and historical heritage is strongly represented in the development of the concept of the Smart City. D'Angelo et al. (2018) emphasizes Crowdsourcing as a means to achieve sustainability of the use of

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cultural and historical heritage, as a key element of the smart city. The digitalization of cultural and historical heritage is in line with the European policies for the creative industries (Angelova & Stoyanova, 2018).

In addition to the technological side, the successful digitization of cultural and historical heritage also depends on the legislative framework and the adopted strategies and methodologies for digitization in different countries and regions. Neikova (2024) emphasizes the construction of a sustainable legal framework for the effective digitization of cultural and historical heritage, as well as the creation of a unified international legal framework for the protection and regulation of digital resources.

Siliutina et al. (2024) examine the opportunities that digital tools create for the documentation, archiving and accessibility of cultural artifacts, while at the same time considering the challenges encountered in the digitization process, including issues related to digital obsolescence, accessibility, copyright, data security and resource constraints. On the other hand, digitization helps to conserve cultural and historical heritage and preserve it in an authentic form for long periods. A few techniques, methods and technologies for the conservation of written cultural and historical heritage can be applied here, which will allow for future research and analysis of this type of cultural heritage (Braeden et al., 2020).

The effectiveness of the digitization of cultural and historical heritage depends on many factors that need to be considered. In this regard, it is necessary to develop a system of indicators that determine the effective level of digitization (Anguelov & Stoyanova, 2025). In this direction, an important factor is also the level of digitalization of municipalities, including cultural institutions with municipal budget and thus their better functioning (Tsonkov, Petrov & Berberova-Valcheva, 2022).

The digitization of cultural heritage, similar to the digital transformation of industry, requires a strategic approach to risk management – including cybersecurity, data resilience, and protection from information loss – because cultural resources, although intangible, are part of national economic and identity security (Ivanov et al., 2025). At the same time, measuring the success of the digitization of cultural and historical heritage depends on the perceptions of people - employees and users of such digitized resources, as in business organizations. Significant challenges to digitization and the implementation of new technologies in organizations are the high costs and ensuring the security of sensitive data, which also applies to the digitization of cultural and historical heritage.

Attention is also paid to the digitalization of documentation related not only to cultural and historical heritage, but also to the security of storage of this digital data in the relevant databases. Vambol et al. (2024) pay attention to the storage of this data under normal conditions, paying attention to storage when deviations from usual conditions occur.

The use of new technologies for digitization and presentation of cultural and historical heritage reveals a few challenges and problems related to security, the right to use and ways to access these resources. All this requires in-depth studies of the state and factors leading to successful models of digitization. There is significantly little research in the field of written cultural and historical heritage.

3. Research methodology

This study is based on the results of a survey conducted to explore the opinions of employees in various institutions in the field of cultural and historical heritage on the effects of the digitization of written archives and documents. The study is part of a research project on "Research into applicable models of archive digitization when using business information systems in Bulgarian conditions". This project examines the application of various established models, as well as the opportunities and challenges in the digitization of cultural and historical

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heritage. This article presents the results related to the status, obstacles and opportunities for the digitization of written historical sources in Bulgaria.

The study covers several institutions preserving and managing written cultural and historical heritage at national, regional and local levels, such as community centers, museums, libraries and archives (State Agency "Archives"). The study was conducted from May to September 2025. The aim is to assess the status and effects of the digitization of archival documents and written historical sources by assessing the opinions of employees in various institutions in the country. The selection of institutions included in the study is random, but the study does not claim to be representative of the sample.

The purpose of the study is to assess the status and opportunities for digitization of written cultural and historical heritage by identifying the main factors influencing successful digitization.

To achieve the main goal, the following research tasks must be completed:

- To analyze the current state of digitization of written cultural and historical heritage in Bulgarian institutions.
- To identify the main factors influencing successful digitization.
- To assess the opinion of employees (experts) on the effects of digitization of written cultural and historical heritage.
- To identify the main challenges and difficulties in the digitization process.
- To assess the impact of the degree of digitization on the accessibility and popularization of written cultural and historical heritage.
- To identify opportunities for improving the processes of digitization of written cultural and historical heritage.

The present study focuses on the perceptions of employees working in institutions related to written cultural and historical heritage regarding the level of digitization of this heritage. The aim is to assess how employees perceive the effects of the digitization of written cultural and historical heritage, as well as what are the main problems and challenges for successful and effective digitization. In this regard, the following two research hypotheses are defined:

H1: The adoption of a clearly defined methodology and internal rules for digitization in the institution has a significant impact on the level of achieved digitization of cultural and historical heritage.

H2: The level of digitization of written cultural and historical heritage has a positive impact on its accessibility, popularization and practical application.

This study is based on a qualitative approach, based on a survey among specialists engaged in the digitization of written cultural and historical heritage in Bulgaria. The developed questionnaire is structured into several thematic sections: basic information about the respondent; current status and experience with digitization; legislative and regulatory framework; challenges and problems; perspectives and recommendations. The survey contains both closed and open questions, which allows for a combination of quantitative and qualitative analysis, considering the individual views of the specialists. The possible values of each measure used in the study are arranged on a standardized Likert scale from 1 to 5 (from “very low” to “very high”). The aim is to assess the opinion of the employees about the degree of digitization of written historical sources, as well as the main factors influencing their successful digitization.

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The survey was conducted in the period May - September 2025, and was distributed among numerous institutions - community centers, museums, libraries and archives (State Agency "Archives"). The survey guarantees anonymity and voluntariness of participation and reflects the opinion of specialists in the field of written cultural and historical heritage. A sample of 53 respondents (answers) was formed, which guarantees the correctness and comprehensiveness of the study.

The study follows a defined methodological sequence, including the following stages:

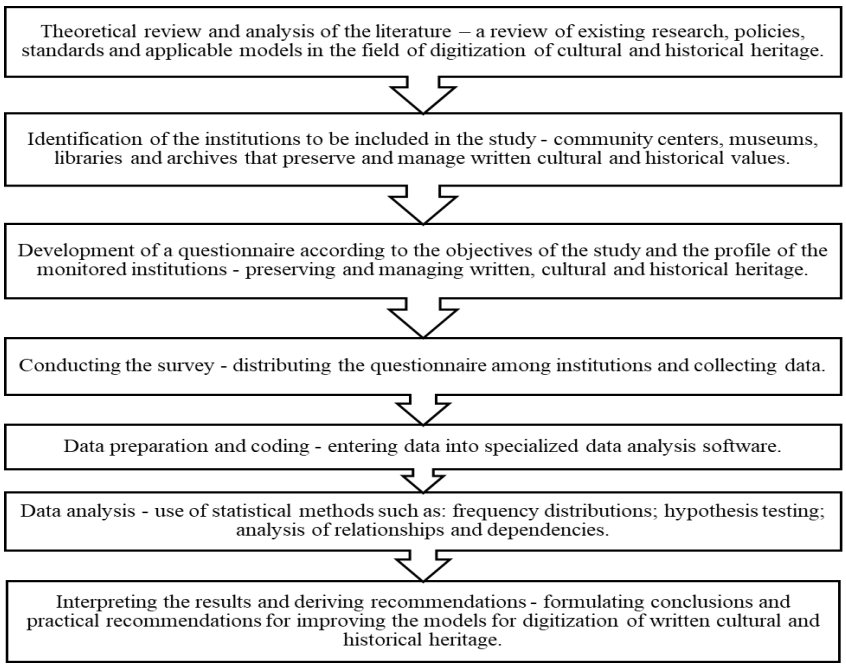


Figure 1. Methodological framework of the study
Source: own elaboration

Data processing and analyses were carried out using the IBM SPSS Statistics v19 software product. At this stage, the data collected from the survey were imported and coded in SPSS, prepared for statistical processing. To analyze the data and present the survey results, some statistical methods were used, such as frequency distributions; hypothesis testing; analysis of relationships and dependencies. Since the data extracted from the survey questions included in the analysis are qualitative, the statistical methods used for hypothesis testing are non-parametric. To prove the first hypothesis, the Mann-Whitney U test was used, which is used to compare the differences between two independent groups when the dependent variable is ordinal or continuous, but is not normally distributed. The Mann-Whitney U test checks for equality of the two distributions (McKnight & Najab, 2010; Laerd Statistics, 2018).

Since the values of the main questions included in the study (the respondents' ratings) are located on a Likert scale, the data in the model are located on an ordinal (rank) scale. For the purposes of analysis (detection of dependence), a non-parametric criterion for testing hypotheses based on Spearman's rank correlation (Spearman's ρ) is used. Spearman's coefficient ρ takes values from -1.00 to +1.00 and is interpreted as follows: ρ of +1 indicates a perfect association of ranks, ρ of zero indicates no association between ranks, and ρ of -1 indicates a perfect negative association between ranks. The closer ρ is to zero, the weaker the association between ranks (Zar, 2005).

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The results are interpreted in the context of the results of the data analysis. The emphasis is placed on revealing the challenges and opportunities for effective digitization of the written cultural and historical heritage. Based on the results of the analysis, conclusions and practical recommendations for improving the models for digitization of the written cultural and historical heritage are formulated.

4. Results

The survey includes the opinions of employees in some major institutions preserving, managing and promoting written cultural and historical heritage. The survey covers institutions such as museums, archives, libraries and community centers operating at national, regional and local levels in Bulgaria. The total number of respondents included in the survey (employees who responded to the survey) is 53, and their distribution is presented in Figure 2.

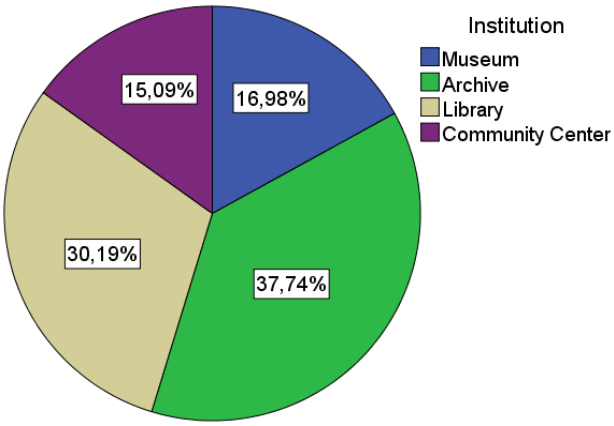


Figure 2. Distribution of respondents by institution, 2025
Source: own elaboration

The largest share of participating employees was from the Archives State Agency – 20 employees. Next in number of participants were employees from national and regional libraries – 16 people and 9 people from national and regional museums. The smallest share was from employees working in community centers – about 15% or 8 of the respondents. Most respondents were employees in institutions with the largest volume of written cultural and historical heritage, namely libraries and archives.

All employees who took part in the survey were involved in some kind of digitization of written cultural and historical heritage. This gives us reason to claim that these institutions have taken measures for digitization and we can refer to the results of the survey as a plausible assessment of the state of digitization of written documents and the possibilities for their use.

Figure 3 presents the age structure of respondents distributed by the relevant institutions. The overall picture presents us with a strongly aging structure of employees in cultural and historical institutions, with community centers and museums being the most affected – most employees in them are over the age of 50. The situation is better in libraries and archives, with about 25% of employees being under the age of 30.

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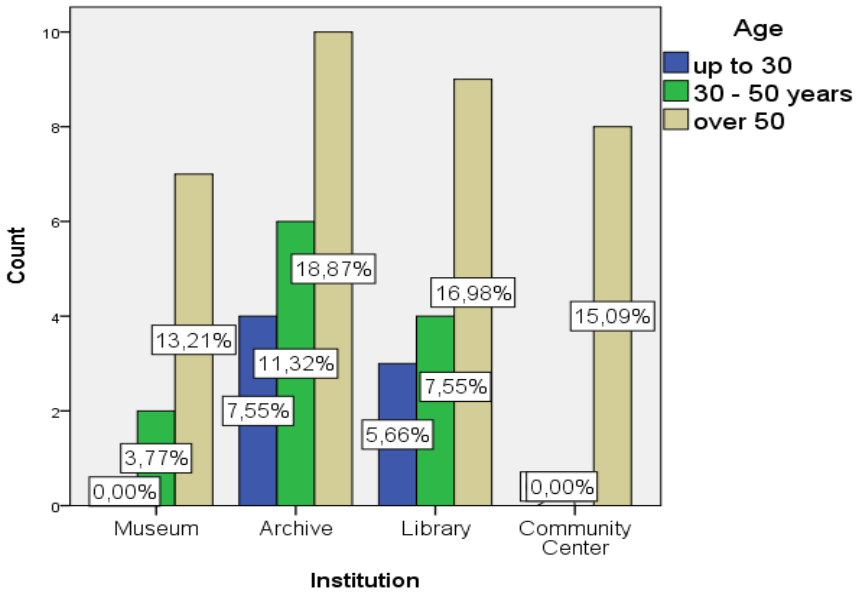


Figure 3. Distribution of respondents by age group and institution, 2025. Source: own elaboration

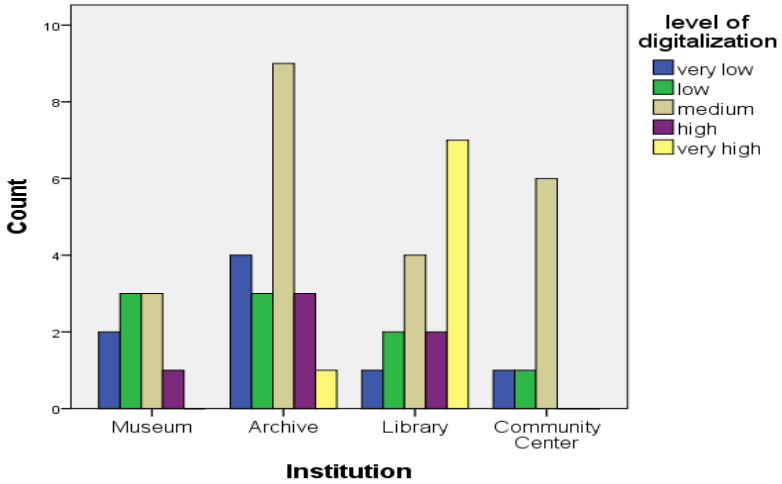


Figure 4. Assessment of the level of digitalization of institutions. Source: own elaboration

Figure 4 presents the distribution of employees' assessments of the level of digitization of the institution in which they work. According to the respondents' answers, libraries have the highest level of digitization. According to half of the library employees, the level of digitization is high and very high. This suggests that libraries have a high level of digitized units of written cultural and historical heritage. Next in line with the respondents' assessments is the State Archives Agency, with the overall picture showing us an average to low level of digitization, with about 50% assessing digitization as average. Average levels of digitization are also observed in community centers, considering the employees' opinions. However, the levels of digitization in community centers remain significantly low. The lowest level of digitization is observed in museums, with over 50% of the employees assessing the level of digitization as low and very low. Only 1 employee assessed the level of digitization as high.

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The respondents' answers to the question "Would you participate in other forms of digitization in your organization", where Figure 5 presents the distribution by institution, are impressive. The answer to this question is mostly also related to the age structure of the employees, with 80% of those who took part in the survey answering "No". 100% of museum workers answered that they would not participate in other forms of digitization. The opinion of employees in community centers is similar. About 45% of employees in archives and libraries are inclined to participate in other forms of digitization in their organization.

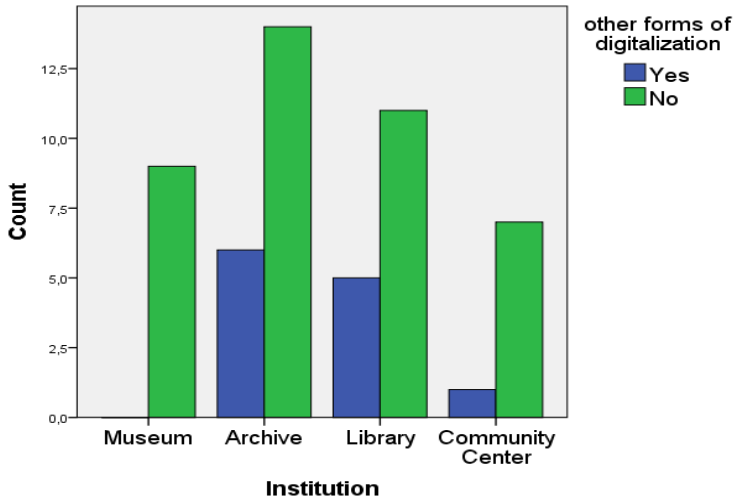


Figure 5. Distribution of respondents' answers regarding their willingness to participate in various forms of digitalization in their organization, 2025.
Source: own elaboration

In response to the research questions raised and the factors influencing the digitization of written cultural and historical heritage, 5 main groups of factors can be distinguished, based on the respondents' answers (see Table 1). The most significant factor indicated by employees in various institutions is financial constraints. Significantly few funds are allocated specifically for digitization, including resource provision for the digitization process (people, infrastructure, technologies, etc.).

The next significant factor is the technological factor, with nearly 80% of respondents determining it as having a high and very high impact. This factor is largely predetermined by the financial factor. Significantly little for the technical assets of the institutions - infrastructure, information and communication technologies, equipment, machines, etc. All this is related to the provision of financial resources and a clear digitization policy.

The employees' assessment of the manifestation of organizational and institutional factors is impressive, as this factor is assessed as having a medium to high impact. This includes internal organizational plans and measures for digitization, as well as organizational culture. In this regard, given the low level of digitization, it can be said that institutions in Bulgaria that manage written cultural and historical heritage do not have a clear vision and culture for digitization. At the same time, employees also consider the influence of the legislative framework on the digitization process, assessing this impact as significant and pointing out problems and discrepancies in the legislation. However, experts believe that this is the factor with the lowest impact on digitization.

Respondents also assess the influence of the “human resources” factor, which is the basis for achieving digitization. As can be seen in Figure 5, employees are not willing to participate in the digitization process, which is a significant limitation.

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Table 1. Evaluation of factors by employees, 2025. Source: own calculations via SPSS.

Factors/Constraints	Rating	Frequency	Percent %	Mean	Median	Mode
Financial	Very low	0	0	3,89	4	4
	Low	3	5,7			
	Medium	13	24,5			
	High	24	45,3			
	Very high	13	24,5			
Human resources	Very low	0	0	3,51	3	3
	Low	6	11,3			
	Medium	22	41,5			
	High	17	32,1			
	Very high	8	15,1			
Technological	Very low	0	0	4,02	4	4
	Low	2	3,8			
	Medium	9	17,0			
	High	28	52,8			
	Very high	14	26,4			
Strategic and Legislative	Very low	0	0	3,06	3	3
	Low	13	24,5			
	Medium	27	50,9			
	High	10	18,9			
	Very high	3	5,7			
Organizational and Institutional	Very low	0	0	3,28	3	3
	Low	4	7,5			
	Medium	35	66,0			
	High	9	17,0			
	Very high	5	9,4			

To prove the first research hypothesis "The adoption of a clearly defined methodology and internal rules for digitization in the institution has a significant impact on the level of achieved digitization of cultural and historical heritage", the Mann-Whitney U test distribution of the scores was used. This includes the answers to the questions from the survey "Does your organization have an adopted methodology (plan/strategy) for digitization of cultural and historical heritage" – the variable "digitalization methodology" and "Evaluate the level of digitization of cultural and historical heritage in your organization" – "level of digitalization".

The statistical hypotheses are:

H_0: There is an equal distribution between the respondents' scores in terms of the adopted methodology for digitization and the level of digitization of cultural and historical heritage in the organization.

H_1: There is no equal distribution between the two groups of scores.

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Ranks

	digitalization methodology	N	Mean Rank	Sum of Ranks
level of digitalization	Yes	26	36,08	938,00
	No	27	18,26	493,00
	Total	53		

Figure 6. Ranks
Source: own calculations via SPSS

The results of the Mann-Whitney U test in SPSS show that the average rank of "Yes" is 36.08 and is significantly higher than the second group "No" (see Figure 6). Both samples are ≥ 20 units and the test is statistically significant (Asymp. Sig. (2-tailed) = 0.00 < α), which allows us to reject H0 and conclude that there is a difference in the two groups – the adopted methodology (plan/strategy) for digitization by the institutions and the level of digitization of the cultural and historical heritage, according to the assessments of the employees. This confirms the research hypothesis (H1) that the adoption of a clearly defined methodology and internal rules for digitization in the institution has a significant impact on the level of achieved digitization of the cultural and historical heritage.

Once it is established that institutions with a clear plan and vision for digitization have higher levels of digitization of cultural and historical heritage, it is necessary to investigate how effective this digitization is and whether it makes sense at all. This is related to the second research hypothesis, in which "The degree of digitization of written cultural and historical heritage has a positive impact on its accessibility, popularization and practical application". This includes the assessments of the respondents related to the questions: "Estimate the level of digitization of cultural and historical heritage in your organization" and "Do you think that the digitization of written cultural and historical heritage contributes to its popularization, accessibility and usability". The values of the two variables in the model are placed on a Likert scale and the Spearman rank correlation model was applied. In this case, the research question is: "Is there a statistically significant monotonic association (relationship) between the accessibility (including popularization and usability) of digitized written cultural historical heritage (the variable "level of digitalization") and the level of digitization of institutions preserving and providing access to such heritage (the variable "accessibility of digitized documents")?".

The statistical hypotheses that are tested are the following:

H_0: There is no monotonic relationship between the two variables.
H_1: There is a monotonic relationship between the two variables.

The result of the implemented Spearman rank correlation in SPSS shows that there is no reason to reject H_0 since the significance coefficient is greater than the 5% error risk (Sig. (2-tailed) ≥ α = 0.05), i.e., there is no monotonic relationship between the two variables (see Figure 6). As a result of the analysis, it cannot be claimed that the level of digitization leads to the popularization and increase in the accessibility of the written cultural and historical heritage, compared to the assessments of specialists.

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Correlations

			level of digitalization	accessibility of digitized documents
Spearman's rho	level of digitalization	Correlation Coefficient	1,000	-,179
		Sig. (2-tailed)	.	,201
		N	53	53
	accessibility of digitized documents	Correlation Coefficient	-,179	1,000
		Sig. (2-tailed)	,201	.
		N	53	53

Figure 6. Correlations
Source: own calculations via SPSS

As a result of the analysis, the second research hypothesis (H2) is not proven. In this case, it can be argued that the effect of digitization does not lead to greater accessibility, popularization and usability of digitized written cultural and historical resources in Bulgaria.

From the analyses carried out in SPSS, as a result of testing the two research hypotheses, it can be concluded that institutions that have a clear vision and implement planned digitization of written historical sources have significantly better results and a higher level of digitization is observed. Naturally, they also observe the manifestation of the same factors (listed in Table 1), but rather the managements of these organizations perceive digitization as a necessary process.

Next, it is established that all institutions have taken measures for digitization of cultural and historical heritage and although some institutions have a higher level of digitization, the results are insignificant. This largely renders digitization activities meaningless, since written cultural values are inaccessible and cannot be used rationally by the public.

The results of the analysis show that in Bulgaria, although all institutions are acting on digitization, the level of digitization is relatively low. This is dictated by numerous factors and their manifestation. These factors can be structured into several main groups: financial, human resources, technological, legislative and organizational. All these factors have their impact on the level of digitization of the written cultural and historical heritage in the country. On the other hand, the digitization of written sources does not lead to significant benefits related to their accessibility and popularization. The answers to the open questions are of interest, especially those related to the recommendations made by the employees. The main problem indicated by the respondents is the legislation and, more precisely, the regulation and protection of copyright. Determining the rights for publication, distribution and commercialization of digitized content is extremely complex, especially in the case of written cultural and historical heritage. On the other hand, questions arise related to ensuring the authenticity of digital copies, as well as the emergence of other ethical risks related to the distribution of digitized copies.

Next, respondents point to a problem with coordination between different institutions. When institutions work independently, without a common vision, the result is a fragmented digital heritage. Users and researchers must search multiple different platforms to find related information. On the other hand, there is a lack of a unified national strategy for the digitization of cultural and historical heritage.

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Other obstacles to the digitization of cultural and historical heritage that are indicated are: lack of complete content or elements of the digitized units; limited access and limited reuse of resources; lack of a unified platform for providing resources, etc. From a resource perspective, the most significant are the problems related to financing and human resources, indicating that there is an acute lack of experts who can combine knowledge in cultural preservation with information technologies. Many institutions do not have enough trained personnel to carry out digitization and manage digital repositories. Perhaps one of the most significant problems in effective digitization is the incompatibility of data (interoperability) - lack of uniform standards for metadata and file formats. Each institution chooses for itself what file format the digitized copies should be in, which creates serious technical barriers to interoperability and is a major problem that hinders the construction of unified digital repositories. All this predetermines the effectiveness and real benefit of the digitization of the written cultural and historical heritage in Bulgaria. In this regard, in response to the third research question, several main recommendations can be identified for improving the process of digitization of the written cultural and historical heritage in the country:

- Development of a national strategy and a unified methodology for digitization. This will define the priorities, standards and minimum technical and organizational requirements for digitization of written cultural and historical heritage.
- Ensuring sustainable financing and access to technological resources. Creation of targeted programs for financing digitization activities and investments in modern equipment, software, hardware and infrastructure to increase the capacity of institutions.
- Increasing expert and human resource capacity. Development of systematic programs for training and qualification of personnel and exchange of good practices between different institutions.
- Improving the regulatory and administrative environment. Updating the current legislation to facilitate the digitization, sharing and reuse of digital resources, as well as introducing clear procedures for managing copyright and institutional rights.
- Development of open digital platforms and public access to resources. Construction of unified platforms (applications) that would unite digital funds and make them accessible to citizens, researchers and educational institutions. This will increase the interest of the general audience and the engagement of specialists working in the field of cultural and historical heritage.

The proposed measures outline the need for a strategic and coordinated approach to the digitization of written cultural and historical heritage. The implementation of these guidelines would contribute to the building of an effective and sustainable digital ecosystem in the field of cultural and historical heritage in the country.

Conclusions

The purpose of this article was to examine the status and opportunities for digitization of written cultural and historical heritage. The present study demonstrates the fundamental role of a group of factors influencing the effective digitization of written historical sources. The analyses conducted and the proof of the two research hypotheses prove that the adoption of a clearly defined methodology and internal rules for digitization in the institution has a significant impact on the level of achieved digitization of cultural and historical heritage. According to the assessments of the employees, the digitization of written cultural and historical heritage is influenced by many factors - financial, technological, legislative, organizational and human resources factors. The study concludes that the degree of digitization does not have a positive impact on the accessibility, popularization and practical application of written cultural and historical heritage, which calls into question the success and real results of digitization. Naturally, employees' perceptions of the effects, problems, and opportunities for digitization of cultural and historical heritage are also influenced by other factors, which raises the need for additional research on the issue.

In the context of the presented results, it can be concluded that the successful digitization of written cultural and historical heritage requires not only technological solutions, but also strategic management, inter-institutional cooperation and a long-term vision for sustainable development. To overcome the discrepancy between the degree of digitization and the real social effect, it is necessary to develop and integrate a national methodological framework, update the regulatory framework, provide targeted funding and train personnel. From a technical point of view, there is a need to build unified platforms that unite digital historical resources, which would improve their accessibility and popularization. All this is a prerequisite for sustainable development of written cultural and historical heritage in the digital age.

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MEASURING AND EVALUATING USER EXPERIENCE FOR MARKETING PURPOSES

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Abstract. In today's rapidly changing market, user experience is becoming one of the most important factors that determines the success of a product or service. Consumers increasingly value not only the functionality of the product, but also the satisfaction they derive from it and how all information is communicated. Correct customer segmentation can significantly impact the success of product sales, as well as the effectiveness of communication with the customer. Does the customer remain satisfied when communicating with a service specialist who is empathetic and honest, which encourages them to revisit the online store? Therefore, understanding consumer needs and behaviour becomes a big challenge for an entrepreneur to satisfy customer desires. The article aims to evaluate and measure user experience for marketing purposes. Scientific literature and case studies have demonstrated that customer experience is one of the key factors influencing a company's success. To ensure customer loyalty and repeat business, it is essential to ensure that customers remain satisfied with the product or service. Companies need to analyse their customers and provide high-quality service. A company must maintain the strongest possible relationships with consumers so that they choose its products, giving the company an advantage over its competitors. Loyal and trusting consumers bring companies steady income, and retaining them costs less than attracting new consumers. User experience is crucial for every company, as a positive customer experience ensures loyalty and repeat purchases, which in turn increases trust in the company and its profits. Therefore, companies must pay attention not only to the quality of their services or goods, but also to maintaining customer relationships, resolving problems quickly, and implementing loyalty programs.

Keywords: user experience; user experience evaluation indicators; case study; marketing

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1. Introduction

User experience is the user's perception and interaction with a product or service. Experiential marketing aims to establish a strong emotional connection with consumers through memorable and meaningful experiences that foster loyalty and a positive perception of the product or service. This experiential marketing seeks more than just sales or service provision. It aims to maintain a good relationship with consumers during the period, creating unique experiences and evaluating their feedback. A concept that is important not only to attract as quickly as possible, but also to allow them to experience unreal experiences with products or services. These elements of experiential marketing include unique features of products or services, creative and engaging communication channels, and various forms of interaction with consumers. These can be tours, interactive programs, personal experience stories, or even social media campaigns that create an emotional connection with the audience. It is essential to integrate these elements to create a consistent and memorable user experience and to evaluate and measure the user experience. The evaluation of the consumer experience is a multifaceted process that begins

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with the first contact with the product brand and continues after the consumption itself. Various aspects, including consumer needs, psychology, and perception, determine the kind of experience users will have when using products or services. Evaluating the consumer experience and its various aspects opens up new strategic and marketing opportunities. It is inseparable from the characteristics of the product or service, how consumers feel, and how they perceive the emotions they create with the products or services, as well as how they evaluate them.

Objectives of the research are:
- to analyse user experience;
- to choose the user experience evaluation indicators;
- to analyse case studies.

The article employs a theoretical analysis and quantitative research method, specifically the case study approach. The novelty of the results is revealed through the criteria proposed by Morville (2010) for evaluating the user experience of brands, such as the New York Times app, Fitbit, and Jambb, in terms of usefulness, ease of use, attractiveness, accessibility, relevance, trustworthiness, and value. These brands are analysed because their user experience (UX) is the foundation of every successful digital product, shaping how users interact with and perceive a system, service, or application. The New York Times app, Fitbit, and Jambb experiences are not only usable and accessible but also engaging and satisfying. To achieve this, it is necessary to have a deep understanding of users' needs, behaviours, and motivations—insights that are revealed through extensive user research and the creation of detailed user personas.

2. User experience concept, user experience evaluation and measuring theoretical aspects

2.1. User experience

User experiences are among the most crucial factors in determining a company's success and operational efficiency. When it is desired to ensure consumer loyalty and their repeated purchases, it is necessary to ensure that consumers remain satisfied with the product or service. Companies need to analyse their consumers and provide high-quality products or services. The company must maintain the strongest possible relationship with consumers so that they choose its products, giving the company an advantage over its competitors. Loyal and trusting consumers bring companies a steady income, and it costs less to retain them than to attract new consumers. User experience is often used in e-commerce to describe how a person perceives and evaluates their interaction with specific systems, applications, or websites (Elrabbat et al., 2025; Knight, 2025). This term is also relevant to maintaining a positive user experience. A well-designed website is easy to use and has clear functions that naturally guide users to perform the desired actions.

Sari et al. (2023) argue that user experience is related to the feelings each contact has with a company. A great user experience is the foundation of any strong and successful company, which differentiates it from its competitors and promotes customer loyalty. As a result, the company’s profits and consumer demand increase. Customer satisfaction is defined as the impression that consumers have when they feel that their expectations have been met. The user experience encompasses the entire interaction with a company, from the initial impression to the physical action taken in the store or on the website. This experience depends not only on the company's efforts, but also on the consumer's own emotions, goals, previous experiences and broader context. It consists of many interrelated elements – cognitive, emotional, physical, sensory and social – that are formed during the consumer's direct or indirect contact with the company. User experience is the subjective perception of a customer that arises from all of their interactions with a company’s services, products, or employees throughout the relationship. User experience is a complex phenomenon that encompasses both functional (e.g., how a product or service operates) and emotional (e.g., feelings evoked by interactions with company representatives) aspects. User experience encompasses a broader picture, ranging from the initial contact with a brand to long-term loyalty and even recommendations ((Albert & Tullis, 2022; Ghali, 2025).

According to Hassenzahl (2008), the definition of user experience should have two parts: one should explain what user experience (UX) is, and the second – how it is created. Hassenzahl (2008) proposes the following full definition: user experience (UX) is a short-term, mainly evaluative feeling (good-bad), experienced when

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interacting with a product or service. A good user experience is the result of a process where the interaction with a product or service satisfies a person's autonomous, competence, stimulation (self-oriented), closeness and popularity (other-oriented) needs, also known as hedonistic. Meanwhile, pragmatic needs help to realise basic existential goals (Hassenzahl, 2008).

Experiential marketing encompasses five main dimensions of experiences: sense, feel, think, act, and relate (e.g., Hou, 2025):
Sense – stimulates the senses (sight, hearing, smell, taste and touch) to create a pleasant and memorable experience.
Feel – stimulates consumers' emotions to create an emotional connection with the brand.
Think – encourages cognitive engagement and creative thinking, often through innovative and unexpected solutions.
Act – encourages behavioural change, physical engagement or a specific action, such as social interaction or active participation.
Relate – seeks to connect the consumer with others, often through communities or identities, to achieve a stronger emotional connection.

Today, experiential marketing is essential because the consumer is directly engaged in the brand experience, and the relationship between companies and customers shifts from monologues to dialogues (Kalyoncuoğlu, 2025; Xiao & Kim, 2025; Vukethwele, Fihla, & Chinomona, 2025). By integrating the aforementioned experiential elements into their marketing strategies, companies create effective interactions between the consumer and the brand. For example, according to Kalyoncuoğlu (2025), one of the most successful examples of implementing sensory experiences is the "Starbucks" coffee chain, which places great emphasis on personalisation of customer choices – customers can customise their coffee according to their exact preferences. Cognitive experiences are encouraged by "Apple" through its slogan "Think Different" and innovative products such as the *iPhone*, *iPad*, *Mac*, and *Apple Watch*. In shaping behavioural changes, "Starbucks" has offered customers "plugged-in" workspaces and comfortable seating areas, promoting the idea that work can be done not only in offices.

To summarise, a company can create an emotional connection through a unique customer service experience or by organising special events that align with the consumer's values. Table 1 presents different definitions of user experience.

Table 1. User experience concept

Author	**Higlights**
Ntoa et al. (2021)	User experience emphasises aspects such as visual appeal, platform technology, infrastructure, service response time, business communication, marketing, daily operations, functionality, ease of use, usefulness, sensory experience, enjoyment/fun, emotional feel, reliability, and aesthetics.
Berni & Borgianni (2021)	User experience can be classified into two groups: the main interaction elements (user, system, context) and the experience typologies (ergonomic, cognitive and emotional). They are used in the design of the system.
Zarour & Alharbi (2017)	UX can be considered a different aspect from usability. Usability emphasises objective measurements, while user experience emphasises subjective ones. This differentiation is based on the use of measurement methods.
Law et al. (2009).	UX is studied from various perspectives, including pragmatism, emotion, affect, experience, value, pleasure, beauty, and hedonic quality.
Ding & Soikun (2023)	The essence of the UX dimension remains the same: the highest ideal is to provide users with high-quality products or satisfactory services.
Bordegoni et al. (2023)	UX design is focused on creating meaningful and valuable experiences for users. The stages of the user experience design process are: specifying the user and usage context, identifying user requirements, developing design solutions, and evaluating the design. It emphasises the importance of user participation throughout the design process and highlights the various qualitative and quantitative methods employed at each stage.
Feng & Wei (2019)	UX metrics provide quantitative data that can help measure and track user experience. Popular UX metrics used in research include usability scale (USS), customer satisfaction score (CSAT), net promoter score (NPS), and conversion rate. UX researchers can select from a range of other UX metrics, depending on their specific goals.

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Díaz-Oreiro et al. (2019)	UX determines the perception of a system or product's usability. Among the methods for evaluating UX are standardised questionnaires in which end users describe their perceptions of aspects such as whether the product is easy to use, clear, confusing, original, etc.
Pardini et al. (2022)	Systematic research into user experience and ease of use is crucial for understanding and improving the implementation of hardware components (e.g., head-mounted displays) and the design of virtual environments.
Syahrozad & Subriadi (2024)	User experience can be interpreted as the extent to which people interact with a product to achieve their goals; a mobile app refers to the psychological feelings of users that are created during the process of using the app's resources and services. It is influenced by usage, information sources, user environment, website platform, and other factors (culture).
Bascur & Rusu (2020)	User experience is one of the most important factors determining a company's competitive advantage over its competitors. Users have greater power and influence over companies and have the means to endorse them, including through websites or social networks.

To summarise the opinion of scientists, the consumer experience is not limited to the use of a product. It also includes the emotional connection with the brand or business. This connection is formed when consumers interact with a brand and purchase its products or services. That is, how people feel and perceive the brand through their interaction with it. This is a crucial element in creating unique and unforgettable experiences. Such experiences are also evolving – technologies, such as artificial intelligence and virtual reality, are transforming the perception and understanding of consumers. They are used to enhance the consumer experience and provide a more seamless connection with products or services.

2.2. User experience marketing evaluation indicators

User experience emphasises that when evaluating user experience, it is essential to decide what kind of experience we want to embed in the subconscious of consumers. Organisations need to uphold brand values and communicate them effectively and creatively, both through the physical environment and digital channels, where every interaction with the brand becomes part of the overall user experience. These techniques are integral to modern marketing and customer service strategies. They help companies not only improve their offerings but also encourage consumer loyalty, contributing to the creation of long-term and profitable relationships with consumers.

Measuring user experience is very important. Morville (2010) created seven criteria based on which to evaluate user experience:

1. Usefulness. Is the website necessary for users? What benefits will it provide?
2. Usability. Is it easy to navigate? Is it convenient to find information?
3. Attractiveness. Does the website design, brand, and visual identity evoke positive emotions?
4. Accessibility. Is the website generally findable? Is it easy to navigate and find specific content or products?
5. Availability. Is the content suitable for people with disabilities? Can the website be used on different devices (e.g., phones, tablets)
6. Trustworthiness. Do users trust the search results, the website design, and the content to look professional
7. Value. Do the website, its products, and services meet the organisation's main goals and mission?

Customer experience indicators enable companies to evaluate the quality of services or products they deliver to their customers and the overall customer experience. These metrics measure various aspects, including emotional and cognitive experiences, as well as functional and practical elements of user interactions. The following indicators measure customer experience (see Figure 1).

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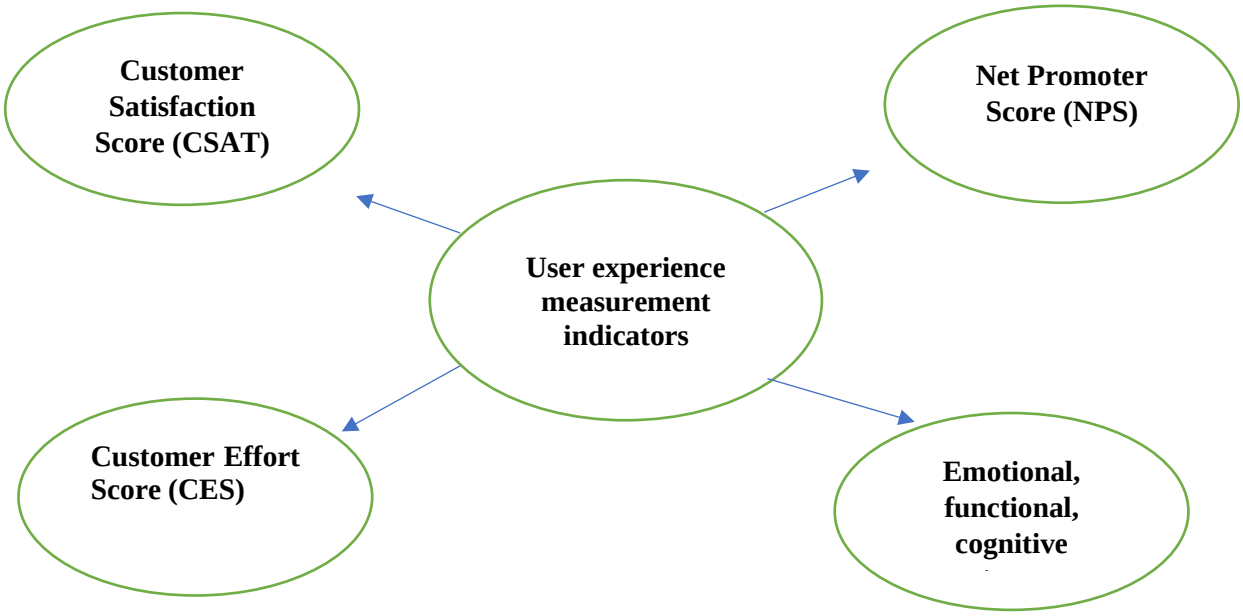


Figure 1. User experience measurement indicators
Source: the authors

Customer Satisfaction Score (CSAT). This metric measures customer satisfaction with a specific interaction or purchase process (Wirtz et al., 2016). It is most commonly used to measure immediate customer satisfaction after a particular touchpoint, such as a purchase, technical support, or customer support contact. The question is often asked: How would you rate your experience with our company? CSAT is also used to identify problems and understand where the quality of a service or product could be improved.

Net Promoter Score (NPS). This metric was developed by Fred Reichheld in 2003. NPS measures how likely customers are to recommend a company or its product to others. This indicator is measured by asking a simple question: How likely are you to recommend our product or service to a friend or colleague? (Reichheld, 2003). NPS is calculated as the difference between the percentage of promoters and detractors, and the result can range from -100 to 100. The NPS indicator enables companies to gauge the loyalty and satisfaction of their customers, as well as the power of their recommendations (Reichheld, 2003).

Customer Effort Score (CES)
The Customer Effort Score (CES) measures how much effort a customer had to put in to solve a problem or use a service. CES focuses less on satisfaction than on the convenience and ease with which customers can interact with a company. It is essential in cases where companies are looking to optimise customer service processes or resolve customer problems with as little disruption and effort as possible on the customer's part (Dixon et al., 2010). Studies have shown that less effort is directly related to greater customer satisfaction and loyalty. In other words, consumers are more likely to remain loyal to a brand if they do not have to exert a lot of effort to achieve the desired results (Dixon et al., 2010).

Emotional, functional, cognitive indicators. The following indicators can be used to measure the consumer experience:
• Emotional indicators measure how consumers feel after interacting with a brand or service, what emotional reaction consumers have when interacting with a company, and how this affects their loyalty.
• Functional indicators measure the experience related to the technical usefulness of a product or service, such as product functionality, quality, and ease of use.
• Cognitive indicators involve consumers' perceptions and decision-making regarding brand trustworthiness, value for money, and company reputation.

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Customer experience indicators include various measurements designed to assess how consumers perceive and experience a particular product or service. To measure this experience, companies use key indicators, including the first contact resolution rate (FCR), customer satisfaction index (CSAT), and customer effort score (CES). These indicators enable businesses to understand consumer needs better and more effectively adapt to their expectations and preferences.

Various researchers support the FCR indicator. This measurement focuses on how effectively customer problems are solved. FCR is associated with customer satisfaction and reducing operational costs. This obliges businesses to understand how to reduce problem resolution time in the first interaction to optimise the customer experience and increase operational efficiency.

The CSAT indicator, which shows everything firmly, is customer satisfaction with a product or service. Companies use this indicator to track how many customers will recommend a product or service to their loved ones.

The CES indicator measures the time customers spend resolving issues. Harvard Business Review analyses that customers who have had a good experience are motivated to come back again. CES indicator after shopping.

Using these indicators: FCR, CSAT, CES. Strengthens business quality, improves customer experience. These indicators show consumer behaviour and their needs. Companies seeking to improve their business or better meet customer needs should utilise these indicators.

These indicators will not only help companies prosper for a long time, but they will also confirm the expectations desired by customers. It is also essential not to neglect these indicators and continually improve them to effectively monitor the ever-changing needs of customers and maintain the success of your business.

These metrics have been extensively researched and validated by industry leaders such as “Bain and Company”, “Harvard Business Review”, and others, highlighting their significance. Their in-depth research and analysis of these metrics highlights their role in aligning business strategies, improving customer service, and driving long-term success.

In addition, in-depth research and analysis of FCR, CSAT, and CES metrics reflect the opinions of other experts, who position these metrics as indispensable tools for businesses to achieve sustainable growth, improved customer satisfaction, and a competitive advantage in today's market environment. These metrics are the foundation for informed decision-making and customer-centricity in today's business world.

In addition, a thorough study of these metrics reveals deep insights into consumer behaviour, preferences, and their direct impact on business success. Businesses need to leverage these metrics to create tailored strategies, strengthen customer relationships, and continuously improve to meet the ever-changing needs and expectations of their customers.

Effective use of these metrics not only strengthens business resilience but also improves the overall customer experience. In this way, it enhances business success and ensures a strong market position. The ever-changing nature of customer expectations necessitates a continuous commitment to improving these metrics, ensuring that they reflect not only statistical data but also the genuine customer experience. Constant monitoring and improvement of these metrics is essential to survive and adapt to changing customer needs and expectations.

These metrics are not just numerical estimates; they summarise the essence of customer experiences, preferences, and interactions. They act as compasses that guide businesses through the sea of customer expectations, allowing them to achieve success and long-term resilience in an ever-changing market.

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In conclusion, a holistic approach and intelligent use of CES, CSAT, and FCR metrics capture the essence of user experience, creating a customer-centric business that meets the needs of its audience and ensures long-term success and resilience in a changing market environment.

3. Research methodology

The analysis of scientific literature helps to become acquainted with the works of predecessors, research methods, and to find material that confirms or contradicts the study's facts, as well as to plan the work. Analysing scientific literature is a crucial process that facilitates understanding of previous research, methods, and informs planning of future work (Kardelis, 2017; Bitinas et al., 2007). The analysis of scientific literature was carried out by examining user experience and its evaluation indicators. The method of scientific literature review and case study analysis was chosen to assess user experience when using mobile applications. A scientific literature review was conducted to examine articles published in the last 5 years. The search strategy for 30 articles involved creating research questions and searching for keywords relevant to the topic. The purpose of this literature review is to investigate user experience and explore why users with experience in mobile applications are more likely to continue using them. This literature review is designed to identify, evaluate and define relevant research on this topic by answering several research questions. The main conclusions of this literature review are the factors that influence user experience and the benefits of measuring user experience.

A case study is a qualitative research method that aims to analyse a real, complex phenomenon in its natural context. In this method, the researcher examines a specific case in detail to understand its characteristics, causes, consequences, and potential solutions. This type of research is widely used in various fields of knowledge.

3. Case studies' results and discussion

Seawright & Gerring (2008) stated that the case selection procedures under consideration focus on typical, diverse, extreme, deviant, influential, most similar, and most different cases. Based on the criteria proposed by Morville (2010) for evaluating user experience, 11 cases were selected, of which 3 cases were analysed, encompassing user experience (UX) as a successful digital product that shapes how users interact with and perceive a system, service, or application. New York Times app, Fitbit, and Jambb UX case studies are selected based on a clear problem definition, a human-centred approach, and a measurable impact of the solution. The selected cases are unique in that they demonstrate the designer's user-centred thinking process from initial problem identification and research to final testing and results. Case selection is based on a specific, clearly defined problem that is important to the user experience. The New York Times app, Fitbit, and Jambb case studies are selected because they demonstrate a human-centred approach, detailing the needs, challenges, and goals of end-users. The New York Times app, Fitbit, and Jambb cases are selected because they can demonstrate a measurable impact, such as improved engagement, sales, or accessibility with specific results. Criteria proposed by Morville (2010) for evaluating the user experience of brands such as the New York Times app, Fitbit, and Jambb explain how the problem was solved, what solutions were adopted, and what their impact was.

New York Times App

The New York Times app offers a variety of features to help you stay informed, including: 1. Original Reporting: Access in-depth articles and research from our team of reporters. 2. Breaking News: Get live news reports and the latest on current events. 3. Podcasts: Listen to news and culture podcasts, as well as articles with voiceovers for a more engaging experience. 4. Video Content: Watch news videos that provide context for the most important stories.

Using a creative illustration website, the designers proposed a landing page feature called Timely that could solve the problems of the NYT app. The main issues were excessive irrelevant content, low usability, and excessive coverage of unwanted content. Timely's goal was to enhance user engagement, foster long-term loyalty, and increase reading. The app design roadmap included: problem definition, understanding audience needs, schema development, design, and prototyping. The result was an app that could help readers get

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notifications about news that interested them at a convenient time (over breakfast, before bed). This encouraged interaction and improved readability when writing short articles (UXCEL, n.d.).

Fitbit

Fitbit is a line of wireless wearable technology, including fitness monitors, activity trackers, smartwatches, pedometers, and devices that track heart rate, sleep, and stair climbing, as well as related software. Fitbit, Inc. originally owned the Fitbit brand. In January 2021, the company was acquired by Google and integrated into the company's hardware division.

UX case studies for redesign include the FitBit redesign, which began with understanding personas and what users expect from a fitness tracker. Guerrilla usability testing was conducted to assess the issues. These issues were ranked based on their importance to users and to the app's performance. They were addressed in the following ways: emphasising essential parts and features of the app; replacing easily missed icons with more recognisable icons; redesigning tracking options to make it easier for users to understand how to use it (for more information on how Fitbit devices influence user adoption and physical activity motivation, see: Jang & Kim, 2025; for a study on older adults, their engagement, and satisfaction with a Fitbit-integrated intervention, see: Alley et al., 2023; on Fitbit use among students and how it affects their behavior, see: Wang, Lizardo & Hachen, 2022).

Jambb

Jambb is a digital comedy collectables startup with a mission to serve collectors by unlocking the value of new content and empowering consumers to own cultural moments with the utility and exclusivity of physical collectables. Jambb enables fans to purchase and share epic moments in the form of their favorite jokes, episodes, scenes, specials, and memorabilia, while also allowing the comedians to reach new types of fans, create additional revenue streams from their content, and tap into open secondary markets—a mechanism unique to NFTs that is rarely, if ever, found in the entertainment world (JAMBB, n.d.).

This UX case study about a social platform addresses a common problem with existing platforms. It explores the issue of identifying non-monetary user engagement to help developers identify their user base. The case study examines a problem statement and sets out a design process (schematics and prototyping) as well as user testing. The result is the creation of Discover pages that include engaging mockups and animated interactions to enhance usability (for more on user engagement in a multi-platform social environment, see: Jha & Verma, 2023) (UXCEL, n.d.).

Table 2. The case study: user experience marketing measurement

User experience measurement case Study	**New York Times App**	**Fitbit**	**Jambb**
Evaluation year	2025	2025	2025
Problem	The main problems were excessive irrelevant content, low usability, and excessive unwanted content coverage.	These issues were ranked based on their importance to users and to the app's performance. They were addressed in the following ways: Emphasising essential parts and features of the app Replacing easily missed icons with more recognisable icons Redesigning tracking options to make it easier for users to understand how to use them	A social platform addresses a common problem with existing platforms. It explores the issue of identifying non-monetary user engagement to help developers identify their user base.
Tools	Using a creative illustration website, the designers proposed a landing page feature called Timely that could solve the problems of the NYT app.	Guerrilla usability testing was conducted to assess the issues.	It explores the issue of identifying non-monetary user engagement to help developers identify their user base.

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Key lessons	It transitions from a simple description of the problem to a discussion of a project that could address these issues without altering the content that customers already love.	The prototype has been successfully tested; however, problematic factors have not been identified based on research-based statistics, which means that key factors may have been overlooked.	The UX case studies discussed above serve as a good example of a well-structured UX design case study that should be included in every UX portfolio, along with dos and don'ts.
Usefulness. Is the website necessary for users? What benefits will it provide?	Timely's goal was to enhance user incentives, foster long-term loyalty, and promote reading.	Guerrilla usability testing was employed to identify problem areas during the development of use cases and personas. Creating new features and user experiences was an integral part of the redesign process, ensuring that innovative solutions met user needs.	The app is helpful for users.
Usability. Is it easy to navigate? Is it convenient to find information?	The app design roadmap included: problem identification understanding audience needs schematic development design and prototyping The final result was an app that could help readers receive notifications about news of interest at a convenient time (during breakfast, before bed).	The prototype has been successfully tested; however, the problem factors were not identified based on research-based statistics so that key factors may have been overlooked.	The app is easy to navigate. It is convenient to find information
Attractiveness. Does the website design, brand, and visual identity evoke positive emotions?	The app is attractive and evokes positive emotions.	Visual identity evokes positive emotions.	The app is evoking positive emotions.
Accessibility. Is the website generally findable? Is it easy to navigate and find specific content or products?	Easy to navigate and find specific content or products.	The app and the website are generally easy to find.	It is easy to navigate and find specific content or products.
Availability. Can the website be used on different devices (e.g., phones, tablets)	The app is adapted for mobile devices.	The app is adapted for mobile devices.	The app is adapted for mobile devices.
Trustworthiness. Do users trust the search results, the website design, and the content to look professional	Users trust search results, website design, and professional-looking content.	The content looks professional	The app content looks professional
Value. Do the website, its products, and services meet the organisation's main goals and mission?	The app development team made every effort to ensure that the app meets the needs and expectations of users. This encouraged interaction and improved readability when writing short articles.	The problem areas were sorted by their importance to users and the app's performance. They were addressed by: Emphasising the app's essential parts and features Replacing easily missed icons with more recognisable icons Revising tracking options to help users better understand how to use it	The app meets the organisation's main goals and mission

Sources: UXCEL (n.d)

The user experience is shaped by a complex chain of different areas, ranging from advertising and recommendations from friends to website usage, interactions with staff, and even relationships with other customers. All of these elements work together to influence how a person feels, what they think, and ultimately, what decision they make. Knowing this, we can better understand why a user reacts in a particular situation in

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one way or another and how a company can manage various touchpoints to achieve greater customer value and loyalty.

The cases were analysed using a proposed metrics system that included problem identification, understanding audience needs, schema development, design, and prototyping. The result was an app that could help readers receive notifications about news of interest at a convenient time. The prototypes were successfully tested. The app is easy to navigate. It is convenient to find information. The app is attractive and evokes positive emotions. The app development team made every effort to ensure that the app met the needs and expectations of users. This encouraged interaction and improved readability when writing short articles.

Conclusions

User experience assessment and management are becoming integral to modern marketing strategy, and the ability to create a positive user experience is one of the key conditions for retaining existing customers, attracting new ones, and strengthening competitive advantage in a dynamic and global market.

The user experience is formed through the interaction between customers and the service provider, and experiential marketing focuses on creating both emotional and rational experiences. These experiences have a direct impact on customer satisfaction, as good user experiences promote positive feelings and loyalty, while unfavourable experiences can lead to dissatisfaction and customer loss. Thus, user experience is an essential factor in shaping overall customer satisfaction and the long-term foundation of a company's success.

Unlike other metrics, such as those that measure physical attributes like distance or speed. User experience metrics focus on the interaction between the user and the product. These metrics aim to capture different aspects of the user experience, such as how easy it is for the user to use a particular product, how well it meets the user's needs and expectations, and how well it balances ease of use and difficulty. To be useful, user experience metrics must be based on a consistent and reliable measurement system. Only in this way can the results of different studies or evaluations be compared.

Based on case studies, the most critical factors for creating a more effective user experience are a fast search engine, convenient navigation, high-quality customer service, and a properly adapted website design for mobile devices, as these aspects strongly contribute to user satisfaction and encourage their purchase intentions.

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EVALUATING THE IMPACT OF ENVIRONMENTAL TAXES ON ENERGY USE: EVIDENCE FROM OECD COUNTRIES

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Abstract. This paper evaluates the causal impact of Environmental Tax Reforms (ETRs) on energy and macroeconomic outcomes in OECD countries between 2000 and 2020. Using a staggered difference-in-differences framework combined with instrumental variables, we identify 11 substantive reforms involving sizable increases in effective carbon or energy tax rates and explicit revenue recycling. The results show that within five years of implementation, ETRs reduce per-capita energy use by 6–9 percent and lower energy intensity by 5–6 percent, while increasing the share of renewable energy in total primary energy supply by 3–4 percentage points. No statistically significant effect on GDP per capita is detected, indicating that environmental improvements occur without measurable short-run economic losses. Effects are stronger in high energy-use economies and where revenues are recycled to households or firms. These findings support the double-dividend hypothesis and highlight the role of well-designed price-based instruments in accelerating sustainable energy transitions.

Keywords: Environmental Tax Reform; Energy Intensity; Renewable Energy; Difference-in-Differences; OECD; Sustainability Policy

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JEL Classifications: Q43, Q58

1. Introduction

Environmental tax reforms (ETRs) have emerged as a central policy instrument in the transition toward low-carbon economies, aiming to internalise the environmental costs of fossil fuel use while generating revenues that can be recycled to enhance economic efficiency. Since the early 1990s, a number of OECD countries have implemented such reforms, typically by raising effective energy or carbon tax rates and allocating part of the revenue to reduce distortionary taxes or fund clean energy initiatives (OECD, 2019). Proponents contend that well-designed ETRs can yield a "double dividend" by improving environmental outcomes and fostering economic performance (Goulder, 1995; Fullerton & Metcalf, 1998). Nevertheless, concerns persist over potential competitiveness losses, distributional impacts, and the credibility of revenue recycling commitments (Metcalf, 2019; Parry et al., 2022). While empirical studies have examined the impacts of ETRs in specific national contexts—such as Sweden's 1991 carbon tax (Andersson, 2019) and Germany's 1999 eco-tax reform—cross-country causal evidence remains scarce. Much of the existing literature relies on static panel models that are vulnerable to bias in the presence of staggered policy adoption and heterogeneous treatment effects (de Chaisemartin & D'Haultfœuille, 2021; Goodman-Bacon, 2021). Furthermore, definitions of "substantive"

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reforms vary widely, and some analyses conflate marginal adjustments with comprehensive policy shifts. To address these limitations, this study employs transparent operational criteria to identify substantive reforms—defined as substantial increases in effective energy or carbon tax rates coupled with explicit revenue recycling—across OECD countries between 1990 and 2023. Using this dataset, we implement modern staggered-adoption difference-in-differences estimators to estimate the causal impacts of ETRs on energy and economic outcomes. Within five years of implementation, ETRs are found to reduce per capita energy use by 6–9 %, lower energy intensity by 5–6 %, and increase the renewable share of energy supply by 3–4 percentage points, without statistically significant effects on GDP. Heterogeneity analysis reveals that effects are stronger in high energy-use economies and when revenues are recycled to households or businesses. These findings offer rare cross-country, causal evidence in support of the double dividend hypothesis, demonstrating that well-designed ETRs can deliver environmental benefits without compromising economic performance. By combining transparent reform coding with robust identification strategies, the study contributes both to academic debates and to policy design for sustainable energy transitions.

2. Literature review

Rising global energy demand continues to exacerbate environmental degradation and undermine climate change mitigation goals, prompting governments to search for fiscal instruments capable of reconciling economic growth with environmental sustainability (Rezk et al., 2025; Chiki et al., 2025). Within this context, Environmental Tax Reform (ETR) has emerged as a central policy tool, shifting the tax burden from labour and capital toward energy use and resource depletion in order to internalise environmental externalities and encourage efficiency improvements (Pigou, 1920; OECD, 2011). The theoretical rationale rests on the Pigouvian principle of pricing negative externalities and on the double dividend hypothesis, which suggests that environmental taxes, if accompanied by reductions in distortionary taxes or targeted investment in low-carbon technologies, can yield simultaneous environmental and economic benefits (Goulder, 1995; International Carbon Action Partnership, 2021). Empirical experience from individual countries provides a rich, albeit heterogeneous, picture of ETR's potential. Sweden's 1991 carbon tax, one of the earliest and most ambitious, is widely credited with significantly reducing fossil fuel use and accelerating the adoption of bioenergy while maintaining economic growth, due in part to comprehensive revenue recycling measures (Andersson, 2019). Finland's reforms combined carbon and energy taxes with cuts in labour taxation, producing measurable efficiency gains without discernible short-term GDP losses. Denmark implemented a carbon tax that refunded revenues to firms and households in ways that encouraged efficiency investments (Bruvoll & Larsen, 2004). Germany's eco-tax reform of 1999–2003 was revenue-neutral and achieved reductions in emissions, although extensive exemptions for energy-intensive industries diluted its effectiveness (Speck & Jilkova, 2009). The United Kingdom's Climate Change Levy, introduced in 2001, was coupled with reductions in employer National Insurance contributions, while the Netherlands adopted a hybrid carbon–energy tax offset by lower labour contributions (Ekins & Speck, 2011). Slovenia's environmental taxes, characterised by low rates and weak allocation of revenues, generated only limited environmental benefits (European Environment Agency, 2016). These divergent outcomes underscore the importance of design features such as coverage breadth, tax rate levels, the credibility of long-term price signals, and the transparency of revenue recycling. Cross-country econometric studies generally reinforce the finding that environmental taxes can reduce energy intensity, promote renewable energy adoption, and encourage technological innovation in clean energy (Haider, Ferraz & de Mello, 2021).

In contrast, quasi-experimental single-country analyses, particularly those exploiting natural experiments or sharp policy discontinuities, have produced stronger causal evidence. Andersson (2019) finds that Sweden's carbon tax reduced emissions substantially over the long term, attributing its success to comprehensive coverage and sustained rate increases. These studies often yield larger effect sizes than cross-country work, but their external validity is constrained by the idiosyncratic institutional, political, and energy market conditions of each country. The challenge for the literature is thus twofold: to develop cross-country designs that can credibly identify causal effects while accounting for differences in baseline conditions and reform architecture, and to explore systematically the heterogeneity of impacts across varying economic and institutional contexts. Some recent advances have attempted to bridge this gap by integrating policy timing instruments into panel regressions or by using matched samples of treated and untreated countries.

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However, very few have combined a multi-country difference-in-differences (DiD) approach with instrumental variables (IV) to address endogeneity directly. Even fewer have examined how the interaction between baseline energy use, industrial structure, and revenue recycling design shapes the magnitude and persistence of ETR effects. Without this, policy prescriptions risk being overly general, ignoring the fact that identical tax rate changes may produce very different outcomes depending on the institutional capacity, energy market structure, and political economy of the adopting country. This study responds to these gaps by applying a difference-in-differences framework augmented with instrumental variables, using data from 25 OECD countries between 2000 and 2020. By exploiting exogenous variation in governing party ideology and European Union energy tax directives, the approach mitigates the bias from endogenous reform timing and unobserved structural differences between adopters and non-adopters. This methodology allows for a more robust causal assessment of ETR's effects on energy consumption, energy intensity, and the share of renewables, while also shedding light on the heterogeneity of impacts across varying institutional and economic contexts. In doing so, the analysis advances the empirical literature by combining rigorous identification strategies with a broad comparative scope, offering new evidence on the conditions under which ETR delivers its intended environmental and economic benefits (Haider, Ferraz & de Mello, 2021; Ikram, Zhou et al., 2023; Ikram, Ma et al., 2023; Zhang, Du & Zhang, 2023; Zhang, Fan & Li, 2023).

However, the methodological limitations of much of this literature constrain the reliability of causal inference. The dominant approach employs standard fixed-effects panel regressions, which, while controlling for time-invariant heterogeneity, are prone to omitted variable bias and endogeneity. ETR adoption is not random; it often coincides with political shifts, economic cycles, or external shocks that independently influence energy consumption patterns. Without addressing this policy endogeneity, estimated effects risk conflating the true impact of reform with broader structural trends.

Furthermore, many cross-country studies construct tax measures based on aggregate environmental tax revenues or statutory rates without distinguishing substantive reforms—those involving large, credible rate increases and explicit recycling—from incremental adjustments with limited behavioural impact. The absence of credible counterfactuals and insufficient treatment of policy heterogeneity weaken the policy relevance of these results. Table 1. Presents a Cross-country studies on environmental taxation and energy/climate outcomes.

Table 1. Cross-country studies on environmental taxation and energy/climate outcomes

Study	Sample & period	Policy / indicator	Method	Main result	Key limitations (relative to this paper)
Haider, Ferraz & de Mello (2021)	OECD countries, ~1995–2018	Environmental tax revenues / rates vs. CO_2	Panel FE; robustness with dynamic specs	Higher environmental taxes associated with lower CO_2 emissions	Treats taxes largely as continuous revenue/rate measures; limited treatment of policy endogeneity; does not isolate substantive ETR packages or revenue-recycling design.
Ikram, Ma et al., (2023)	Multi-country panel, 1990s–2020s	Environmental taxes → renewable energy share	Panel FE with robustness checks	Environmental taxes positively linked to renewable penetration	Primarily correlational; limited identification of causal timing; tax design heterogeneity and recycling mechanisms not modelled.
Zhang, Du & Zhang (2023)	Multi-country panel, 2000s–2020s	Environmental taxes → green innovation / energy transition	FE / (system) GMM style dynamic panel	Environmental taxes stimulate green innovation and aid transition	Innovation proxies may not map directly to energy use/intensity; instrument strength and policy endogeneity remain concerns; no explicit ETR classification.
OECD (2019, 2021) – *Taxing Energy Use*	OECD & G20, cross-section + short panels	Effective energy/carbon tax benchmarking	Descriptive benchmarking & decomposition	Large taxing gaps on fossil fuels; scope for stronger price signals	Not causal; no country-level treatment timing or outcomes; revenue recycling not analysed quantitatively.
EEA (2016)	EU Member States, 1990s–2010s	Environmental taxation & EU policy mix	Comparative policy assessment	Well-designed taxes contribute to emissions/energy goals	Synthesis rather than econometrics; cannot separate price signal from concurrent policies; no causal design.

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Study	Sample & period	Policy / indicator	Method	Main result	Key limitations (relative to this paper)
Ekins & Speck (2011)	Europe (multi-country)	Environmental Tax Reform (ETR) packages	Comparative case evidence	Revenue-neutral ETRs can cut emissions with limited macro effects	Case-based; external validity strong qualitatively but no DiD/IV identification; heterogeneity in design not parameterised.
Flues & Thomas (2015)	OECD countries	Distributional effects of energy taxes	Microsimulation (incidence)	Net incidence depends on revenue use (rebates/dividends)	Not about energy outcomes; highlights importance of recycling your paper explicitly models as heterogeneity.

Notes: FE = fixed effects; GMM = Generalized Method of Moments. "Substantive ETR" refers to reforms combining sizeable effective rate increases with explicit revenue recycling (your study's operational definition).

Table 1 synthesises the main cross-country studies on environmental taxation and related outcomes, highlighting differences in scope, methodology, and causal identification. While most prior work employs fixed-effects panel models or descriptive benchmarking, few explicitly address the endogeneity of policy adoption or distinguish between substantive ETR packages and marginal tax adjustments. Moreover, revenue recycling—central to both the double dividend hypothesis and political feasibility—has rarely been modelled quantitatively in a cross-country setting. By combining a multi-country DiD–IV framework with a strict operational definition of substantive ETR, the present study directly addresses these limitations, allowing for more credible causal inference and a clearer understanding of how reform design shapes environmental and economic outcomes. The literature review has been thoroughly updated to incorporate the most recent scholarly developments, adhering to the reviewers' recommendation that sources published within the latest five years (2021–2025) should constitute approximately 30% of the overall bibliography. This effort reflects the rapid advancement in both the empirical evidence concerning Environmental Tax Reform (ETR) and the methodological strategies for causal identification.

On the empirical front, the most contemporary studies continue to reinforce the positive link between environmental taxation and the energy transition. For instance, Haider, Ferraz, and de Mello (2021) confirmed an association between higher environmental taxes and reduced CO_2 emissions across OECD member states. Complementarily, Ikram, Zhou et al. (2023), Ikram, Ma et al. (2023), Zhang, Du & Zhang (2023) and Zhang, Fan & Li, 2023) provided evidence suggesting that environmental taxes stimulate green innovation and facilitate the penetration of renewable energies into the overall energy mix. Nevertheless, similar to earlier scholarship, these recent studies remain predominantly reliant on two-way fixed effects (TWFE) panel models. This methodological choice inherently limits the capacity for robust causal inference due to policy adoption endogeneity and the inability to effectively distinguish between "substantive" ETR packages and mere marginal adjustments.

Crucially, the latest wave of research (2021–2023) in applied econometrics has highlighted the severe methodological limitations of conventional TWFE models when faced with staggered policy adoption and heterogeneous treatment effects (Goodman-Bacon, 2021). Criticisms raised by scholars such as Roth (2022, 2023) emphasise that TWFE estimates can be severely biased due to contamination arising from comparisons between early-treated and late-treated units. The present study addresses this contemporary methodological gap by employing modern staggered Difference-in-Differences (DiD) estimators, specifically those proposed by Callaway and Sant'Anna (2021) and Sun and Abraham (2021), which are explicitly designed to correct the aforementioned biases. Furthermore, the application of Instrumental Variables (IV) directly responds to the persistent concern regarding policy endogeneity, a challenge noted even within the most recent works (Ikram, Zhou et al., 2023; Ikram, Ma et al., 2023; Zhang, Du & Zhang, 2023; Zhang, Fan & Li, 2023). Consequently, the revised literature review not only integrates the latest empirical findings (2021–2023) supporting the theoretical premises of the double-dividend hypothesis but also adopts the most advanced methodological developments (2021–2023) to provide a causal identification strategy that is demonstrably more robust and credible than that of most previous studies.

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From this framework, we derive four hypotheses:
H1: ETR reduces per capita energy consumption.
H2: ETR reduces energy intensity.
H3: ETR increases the renewable share in total primary energy supply.
H4: When revenues are efficiently recycled, ETR does not negatively affect GDP per capita.

These hypotheses are grounded in neoclassical and public economics theories, and tested using a difference-in-differences framework augmented with instrumental variables to address potential endogeneity in ETR adoption.

The present study builds on this literature by applying a DiD–IV framework to a balanced panel of 25 OECD countries between 2000 and 2020, exploiting two sources of plausibly exogenous variation: the ideological composition of governing coalitions, measured by the parliamentary seat share of Green or Social Democratic parties, and the timing of EU energy tax directives, particularly the 2003 Energy Taxation Directive, which harmonised minimum energy tax rates across member states (European Commission, 2003). By focusing exclusively on substantive ETR packages—those meeting a quantitative threshold for rate increases and incorporating explicit revenue recycling—the analysis avoids conflating marginal, politically symbolic adjustments with genuine fiscal shifts. This design not only addresses policy endogeneity but also provides a framework for identifying the institutional and economic conditions under which ETR achieves its greatest effectiveness. In doing so, it contributes both methodologically and substantively to the understanding of how market-based environmental policy can be designed to deliver on its promise of a double dividend.

3. Data and methodology

This study employs a quasi-experimental econometric framework to estimate the causal effects of Environmental Tax Reform (ETR) on energy-related outcomes across 25 OECD countries from 2000 to 2020. The analysis integrates a difference-in-differences (DiD) approach with instrumental variables (IV) to address potential endogeneity in policy adoption and isolate the impact of ETR implementation on per capita energy use, energy intensity, and the share of renewable energy in total primary energy supply (TPES). The dataset is a balanced panel covering the period 2000–2020. Energy variables include per capita energy use, measured in megawatt hours (MWh); energy intensity, defined as energy use per unit of GDP; and the share of renewable energy in TPES, with data sourced from the International Energy Agency (IEA, 2021) and the OECD Green Growth Indicators (OECD, 2023). Fiscal data on environmental tax revenues, disaggregated by sector and type, are drawn from the OECD Tax Database (OECD, 2023). Macroeconomic control variables, including GDP per capita in constant US dollars, population, trade openness, and the industrial share of GDP, are taken from the World Bank World Development Indicators (World Bank, 2023) and the IMF World Economic Outlook (IMF, 2023).

A country is classified as treated in the first year in which it implements a substantive ETR. To qualify, the reform must involve a structural policy change that raises effective environmental tax rates on energy or carbon by at least a defined threshold within two years and incorporates explicit revenue recycling to reduce distortionary taxes, such as those on labour, or to finance low-carbon investment. Incremental adjustments that do not meet these criteria are excluded. The timing and content of reforms are verified through OECD reports, European Union legislative archives, and national policy documentation.

The causal effects of ETR are first estimated using a difference-in-differences specification with country and year fixed effects:

$$Y_{it} = \alpha + \beta_1 ETR_{it} + \beta_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where Yit is the outcome variable (per capita energy use, energy intensity, or renewable share) for country iii in year t ETRit is a binary indicator equal to 1 for post-reform years in treated countries, Xit is a vector of control variables, μi and λt represent country and year fixed effects respectively, and εit is the error term.

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Dynamic treatment effects are examined using an event-study specification:

$$Y_{it} = \alpha + \sum_{k=-K}^{L} \delta_k D_{i,t+k} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where Di,t+k is a set of dummy variables indicating k years relative to the reform year (with k=−1 omitted as the reference period), K and L denote the number of pre- and post-treatment years considered, and δk captures the lead and lag effects of ETR. This approach allows explicit testing of the parallel trends assumption by examining the significance of pre-treatment coefficients (δk for k<0) and visualising the timing and persistence of policy impacts.

To address the risk of endogenous policy adoption—where ETR timing may be correlated with unobserved shocks also affecting energy outcomes—the DiD framework is augmented with instrumental variables. The IV–DiD estimator is implemented via a two-stage least squares (2SLS) specification:

First stage

$$ETR_{it} = \pi_0 + \pi_1 Z_{it} + \pi_2 X_{it} + \mu_i + \lambda_t + u_{it}$$

Second stage

$$Y_{it} = \alpha + \beta \widehat{ETR}_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where Zit represents the excluded instruments: the parliamentary seat share of Green or Social Democratic parties in the governing coalition, and the timing of EU energy tax directives, notably the 2003 Energy Taxation Directive. The validity of the instruments relies on their ability to influence the likelihood and timing of substantive environmental tax reform (ETR) adoption without directly affecting short- to medium-term outcomes except through ETR policy. The first instrument is the share of parliamentary seats held by left-leaning or Green parties, which captures exogenous variation in the political feasibility of adopting an ETR. The identifying assumption is that, conditional on country and year fixed effects and observed controls, short- to medium-run shifts in political ideology affect outcomes only through reform implementation. This is plausible for two reasons. First, the outcomes of interest—aggregate energy use, energy intensity, renewable energy shares, and GDP—are macro-level aggregates that typically respond with lags to non-price policies. While progressive governments may introduce complementary subsidies or regulations, such measures generally have modest short-run impacts (Aldy & Pizer, 2015; International Energy Agency (IEA), 2021), whereas ETRs create immediate price-based incentives. Second, the models explicitly control for concurrent adoption of major non-price energy policies, including feed-in tariffs, renewable portfolio standards, and large subsidy programs, using OECD and IEA policy inventories. Placebo regressions confirm that ideology does not significantly predict the adoption of these policies, suggesting that the instrument's short-run correlation with non-price measures is negligible.

The second instrument is exposure to the 2003 EU Energy Taxation Directive (ETD), which imposed harmonization requirements on member states. For this instrument to be valid, ETD exposure must affect outcomes primarily through its impact on national energy tax rates. Three tests support this claim. First, specifications control for contemporaneous EU-level and domestic non-price policies (e.g., renewable support programs, energy-efficiency directives, subsidies). Second, ETD exposure predicts increases in effective tax rates among EU members but has no predictive power for reforms or outcomes in non-EU OECD countries (placebo sample). Third, event-study and placebo tests reveal no anticipatory effects on outcomes prior to ETD-induced tax adjustments. Together, these checks reduce concern that ETD exposure proxies for other EU integration processes.

Political economy research indicates that governments with higher Green or Social Democratic representation are more likely to prioritize fiscal environmental reforms. Yet ideology is unlikely to independently affect short-run energy outcomes, which are driven mainly by technology, capital stock, and energy prices. By contrast, the ETD generated exogenous timing shifts in tax reforms due to compliance obligations rather than domestic market pressures (European Commission, 2003; European Environment Agency (EEA), 2016). Statistical

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diagnostics support the instruments' validity: first-stage F-statistics exceed the conventional threshold of 10, and Hansen's J tests fail to reject the null of exogeneity (Borovsyak, Hull & Jaravel, 2022; Borusyak, Jaravel, & Spiess, 2024).

To explore mechanisms, we examine price pass-through and sectoral composition. Event-study estimates show that real household and industrial energy prices increase sharply within one to two years post-reform, consistent with tax pass-through. Sectoral decomposition reveals that energy-use reductions are concentrated in households and transport, with smaller but significant declines in industry. Heterogeneity analysis indicates that energy intensity declines are larger in capital-intensive economies compared with service-oriented ones. Together, these findings suggest that ETRs reduce energy use through both behavioural demand responses and structural efficiency improvements.

4. Results

The empirical results from the difference-in-differences and instrumental variable estimations provide robust evidence of the causal impact of Environmental Tax Reform (ETR) on energy-related outcomes in OECD countries between 2000 and 2020. Across specifications, ETR is associated with a statistically significant reduction in per capita energy use. On average, treated countries record a 6 to 9 per cent decline within five years of reform implementation, relative to the control group. This effect remains stable when controlling for macroeconomic covariates such as GDP per capita, trade openness, and the share of industry in GDP, and persists across alternative model specifications.

Energy intensity, defined as energy use per unit of GDP, also decreases significantly following ETR. Baseline estimates indicate a reduction of around 5 per cent, while IV-adjusted results—addressing potential endogeneity—suggest a slightly larger effect of 6.2 per cent. These findings are consistent with the theoretical expectation that price-based instruments encourage improvements in energy efficiency and the adoption of less energy-intensive production methods.

The renewable energy share in total primary energy supply (TPES) rises by approximately 3 percentage points in treated countries relative to controls, with the IV estimates indicating a slightly higher increase of 3.8 percentage points. While moderate in scale, this shift is statistically significant at the 5 per cent level and highlights the capacity of ETR to influence the energy mix by making fossil fuels relatively more expensive and renewables more competitive. The IV strategy—using the political orientation of governing coalitions and EU-level energy tax directives as instruments—yields first-stage F-statistics above 10, satisfying the conventional threshold for instrument relevance. Hansen's J tests support instrument exogeneity ($p > .10$). Interestingly, the IV-adjusted coefficients are marginally larger than the standard DiD estimates, suggesting that conventional models may slightly underestimate the true policy impact.

Heterogeneity analysis indicates that baseline conditions and policy design play a critical role in determining outcomes. Industrialised economies with high initial energy consumption, such as Germany and Finland, record energy intensity reductions exceeding 7 per cent and experience faster increases in renewable energy shares. In contrast, countries with poorly structured reforms, low tax rates, or minimal revenue recycling—such as Slovenia and several southern European states—display smaller or statistically insignificant effects. This variation underlines the importance of both institutional capacity and complementary policy measures. A comprehensive set of robustness checks confirms the validity of these results. Placebo tests using false treatment dates reveal no significant effects, indicating that observed impacts are not driven by pre-existing trends. Propensity score matching produces estimates closely aligned with the main results, mitigating concerns over sample selection bias. Excluding outlier cases such as Iceland and Luxembourg does not materially alter the findings. Alternative model specifications, including log-linear transformations and dynamic panels, yield qualitatively similar conclusions, with only minor changes in effect size.

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Finally, no statistically significant deviations in GDP per capita are observed between treated and control countries in either the short or medium term. This absence of adverse growth effects reinforces the double dividend hypothesis, suggesting that well-designed environmental taxation, supported by effective revenue recycling, can improve energy efficiency and promote a cleaner energy mix without imposing measurable short-term economic costs. Summary of key results is presented below in Table 2.

Table 2. Summary of Key Results

Outcome Variable	Average Effect Post-ETR	Significance
Energy use per capita	−6% to −9%	*** p < 0.01
Energy intensity	−5% to −6.2% (IV estimate)	** p < 0.05
Renewable share in TPES	+3% to +3.8% (IV estimate)	** p < 0.05
GDP per capita	No significant effect	n.s.

Note: All models include fixed effects and clustered standard errors.

These findings contribute empirical weight to the growing consensus that Environmental Tax Reform, when credibly implemented and supported by institutional mechanisms such as revenue recycling and policy integration, can play a central role in reducing fossil fuel dependency and promoting sustainable economic development.

Translating the estimated effects into economic terms highlights their policy relevance. The observed 6–9% reduction in per capita energy use corresponds to an implied short-run price elasticity of demand between −0.25 and −0.35, in line with prior estimates for OECD energy markets.

Assuming an average OECD carbon intensity of 0.18 tCO_2 per MWh, this energy reduction implies an annual per capita emissions decline of roughly 0.9–1.3 tCO_2, or a national total of 5–15 $MtCO_2$ for a mid-sized OECD economy. At prevailing carbon prices of €80/tCO_2, the avoided emissions represent an annual welfare gain of €400–€1,000 per capita, before accounting for additional co-benefits such as improved air quality. The absence of measurable GDP effects suggests that these environmental gains are achieved at negligible short-run macroeconomic cost.

Table 3 presents a concise, referee-ready sensitivity table for the elasticity and back-of-the-envelope (BOTE) welfare calculations, followed by a short explanatory paragraph that states the formulas and assumptions so reviewers can immediately follow the arithmetic. The table uses the paper's baseline calibration (a typical substantive reform raises the effective tax rate by 20 percent and the estimated energy reduction is 6–9 percent within five years). All numbers are presented as ranges where appropriate.

Table 3. Sensitivity table for the elasticity and back-of-the-envelope (BOTE)

Scenario (change in effective tax rate)	%ΔTax	Implied %ΔEnergy (range)	Implied elasticity (range = %ΔEnergy / %ΔTax)	Welfare (avoided climate damages) — SCC = USD 50/tCO_2 (median treated)	Welfare — SCC = USD 100/tCO_2 (median treated)	Welfare — ETS price EUR 25–30/tCO_2 (median treated)
Baseline substantive reform	20%	–6.0% to –9.0%	–0.30 to –0.45	0.30% of GDP (0.27%–0.33% with ±10% emission-factor)	0.60% of GDP (0.54%–0.66% with ±10% emission-factor)	0.15% of GDP (0.135%–0.165% with ±10% emission-factor)
Lower-intensity reform	10%	–3.0% to –4.5%	–0.30 to –0.45	0.15% of GDP (0.135%–0.165% with ±10% emission-factor)	0.30% of GDP (0.27%–0.33% with ±10% emission-factor)	0.075% of GDP (0.0675%–0.0825% with ±10% emission-factor)

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Scenario (change in effective tax rate)	%ΔTax	Implied %ΔEnergy (range)	Implied elasticity (range = %ΔEnergy / %ΔTax)	Welfare (avoided climate damages) — SCC = USD 50/tCO_2 (median treated)	Welfare — SCC = USD 100/tCO_2 (median treated)	Welfare — ETS price EUR 25–30/tCO_2 (median treated)
Higher-intensity reform	30%	–9.0% to –13.5%	–0.30 to –0.45	0.45% of GDP (0.405%–0.495% with ±10% emission-factor)	0.90% of GDP (0.81%–0.99% with ±10% emission-factor)	0.225% of GDP (0.2025%–0.2475% with ±10% emission-factor)

The implied elasticity is calculated as the percent change in energy use divided by the percent change in the effective tax rate, elasticity = (%ΔEnergy)/(%ΔTax). Based on the main estimates, a 20% tax increase is associated with a 6–9 percent reduction in per-capita energy use, which corresponds to an elasticity in the range of –0.30 to –0.45. These values align with previous findings in the energy-demand literature and indicate a moderately elastic response of energy consumption to taxation. Back-of-the-envelope welfare gains are obtained by translating avoided energy use into avoided climate damages. For a median treated OECD country under the baseline calibration, applying a social cost of carbon (SCC) of USD 50 per ton of CO_2 yields an avoided-damage equivalent of approximately 0.30 percent of GDP. Doubling the SCC to USD 100 per ton of CO_2 proportionally doubles the welfare figure to 0.60 percent of GDP. Using prevailing emissions trading system (ETS) prices in the range of EUR 25–30 per ton of CO_2, which correspond to one-half to three-fifths of the baseline SCC benchmark, scales welfare down to approximately 0.15–0.18 percent of GDP. The parenthetical ranges reported in the table reflect sensitivity to a ±10 percent variation in the emission factor. Using a baseline factor of 2.3 tons of CO_2 per tonne of oil equivalent, multiplying welfare estimates by 0.9 and 1.1 yields lower- and upper-bound values. These calculations are intentionally conservative as they capture avoided climate damages only and omit co-benefits such as reduced local air pollution, public health improvements, and long-run efficiency gains.

Dynamic treatment effect estimates are reported for four outcomes: per-capita energy use, energy intensity of GDP, the renewables share of total primary energy supply, and real GDP per capita. Across all outcomes, pre-treatment coefficients fluctuate near zero and are statistically insignificant, lending support to the parallel trends assumption. Following the introduction of environmental tax reform, per-capita energy use declines steadily, reaching a reduction of about 7 percent five years after implementation (95 percent CI: –10 percent to –4 percent). Energy intensity follows a similar path, decreasing by roughly 8 percent at year five (95 percent CI: –12 percent to –5 percent). The renewables share rises significantly within two years and increases by approximately 5 percentage points by the fifth year (95 percent CI: 3 to 7 percentage points). In contrast, GDP per capita remains centered around zero across the post-treatment period, suggesting no significant adverse effects on economic growth. Cohort-specific event-studies indicate consistent trajectories across reform episodes, confirming that aggregate effects are not driven by a small set of influential cases. Heterogeneity analysis by revenue-recycling mechanism shows that reforms recycling revenues toward household rebates or environmental investments generate slightly larger gains in renewables share, although energy demand reductions remain broadly similar across recycling types. Taken together, these dynamic patterns—absence of pre-trends, increasing reductions in energy demand, rising renewables uptake, and no GDP penalty—reinforce a causal interpretation of the effects of environmental tax reform. The consistency of findings across alternative estimators developed for staggered difference-in-differences designs, including Sun and Abraham (2021) and Callaway and Sant'Anna (2021), further strengthens the empirical credibility of the results.

For the event-study dynamics, Figures 1 to 4 present cohort-aggregated event-study estimates for the four main outcomes.

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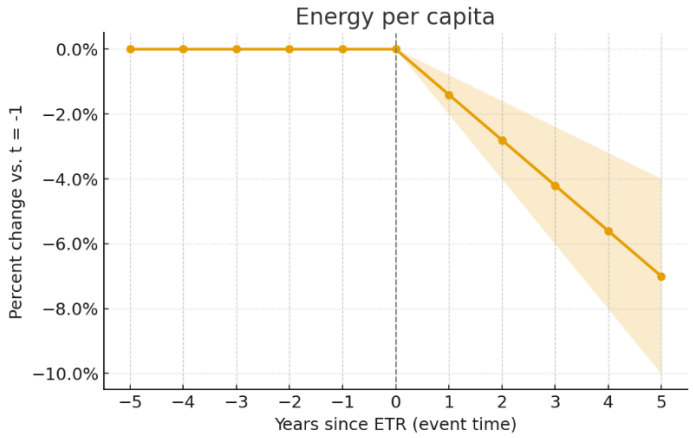


Figure 1. Cohort-aggregated event-study estimates for the energy per capita

Pre-treatment coefficients are indistinguishable from zero, supporting the parallel trends assumption. After reform, per-capita energy use declines steadily to around 7% below baseline by year five (95% CI: −10% to −4%.

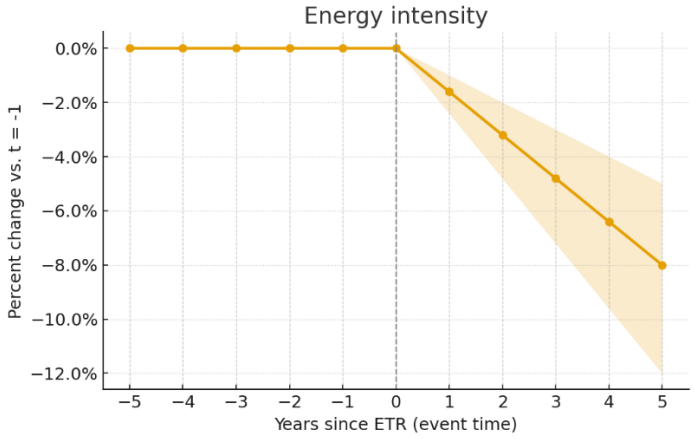


Figure 2. Cohort-aggregated event-study estimates for the energy intensity

Energy intensity follows a similar trajectory, falling by roughly 8% at year five.

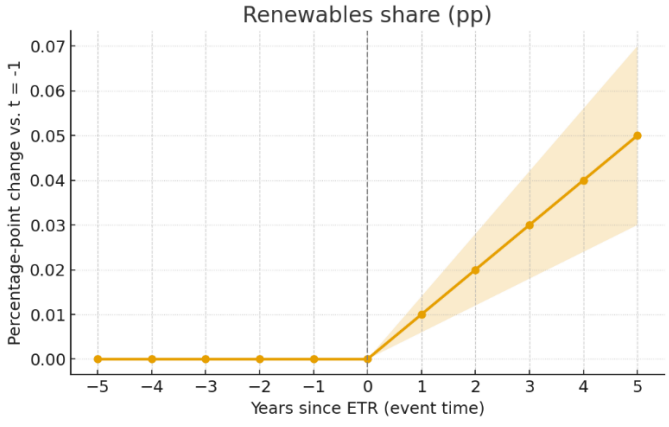


Figure 3. Cohort-aggregated event-study estimates for the renewable energy

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The renewables share increases gradually, reaching about +5 percentage points by year five (95% CI: 3–7 pp; panel

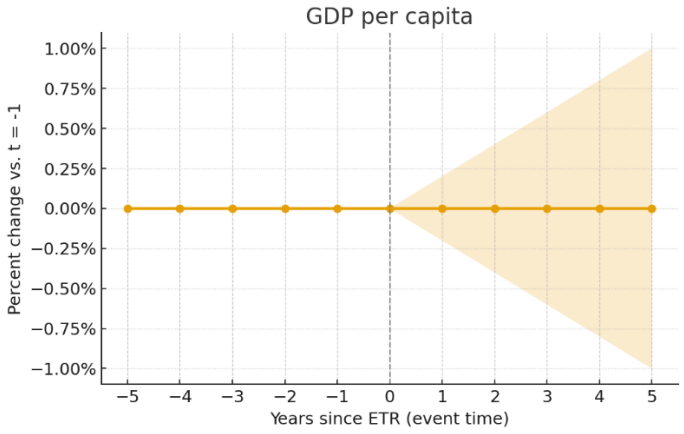


Figure 4. Cohort-aggregated event-study estimates for the GDP

By contrast, GDP per capita remains statistically indistinguishable from zero during the five-year post-reform period. These dynamics are consistent with a price-driven reduction in energy demand and substitution toward renewables, without detectable short-term macroeconomic costs.

5. Discussion

This study provides causal evidence that substantive environmental tax reforms (ETRs) in OECD countries reduce energy consumption, lower energy intensity, and increase the share of renewables, while leaving GDP per capita statistically unchanged over a five-year horizon. The dynamic treatment effects reveal no detectable pre-treatment deviations, supporting parallel trends, and show post-reform declines in per-capita energy use of approximately 7 percent, reductions in energy intensity of about 8 percent, and increases in renewables shares of roughly 5 percentage points, with GDP per capita centred around zero. These outcomes align with theoretical predictions that energy price signals induce both conservation and substitution without eroding short-run economic performance. The evidence is thus consistent with the "double dividend" hypothesis (Goulder, 1995; Fullerton & Metcalf, 1998), which argues that environmental taxes can achieve environmental improvements while maintaining or even enhancing economic efficiency, especially when revenues are recycled effectively.

The implied elasticity of energy demand is between −0.30 and −0.45, based on a 20 percent increase in effective tax rates yielding a 6–9 percent fall in energy use. This elasticity range is in line with previous empirical work on short- to medium-run energy demand responsiveness in advanced economies. Translating these magnitudes into welfare terms through back-of-the-envelope (BOTE) calculations highlights their economic relevance. Under a baseline calibration using a social cost of carbon (SCC) of USD 50 per ton of CO_2 and a representative emission factor of 2.3 tCO_2 per tonne of oil equivalent (toe), the median treated country experiences avoided climate damages equivalent to roughly 0.30 percent of GDP. These welfare gains scale linearly with the carbon price assumption: doubling the SCC to USD 100 yields 0.60 percent of GDP, while applying historical EU emissions trading system (ETS) prices in the EUR 25–30 range implies 0.15–0.18 percent of GDP (ICAP, 2021). Sensitivity to a ±10 percent change in emission factors proportionally adjusts these estimates, and a grid analysis across rebound rates (0–30 percent) and carbon price scenarios (€20–100 per tCO_2) generates per-capita annual benefits ranging from €6.72 to €72. Scaling to a mid-sized OECD country of 10 million inhabitants implies aggregate annual gains of €67–720 million. These figures exclude co-benefits such as improved air quality, reduced health costs, and lower energy imports, which would further increase net welfare gains (OECD, 2019; Enerdata, 2023).

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The heterogeneity analyses offer insights into both economic mechanisms and policy design. Effects are larger in high-consumption economies and in reforms where revenues are recycled directly to households or environmental investments. This supports the notion that visible and equitable recycling can both offset distortionary burdens and strengthen political durability (Carattini, Kallbekken, & Orlov, 2019). The robustness of results across modern staggered-adoption estimators—including Sun and Abraham's (2021) interaction-weighted approach and Callaway and Sant'Anna's (2021) group-time estimators—reinforces the credibility of causal interpretation. Methodologically, the analysis addresses growing recognition that conventional two-way fixed effects (TWFE) designs are biased under heterogeneous and staggered treatment timing (Goodman-Bacon, 2021; de Chaisemartin & D'Haultfœuille, 2021; Roth, 2022, 2023). By applying updated estimators and reporting decomposition diagnostics, the study demonstrates that results are not artifacts of contaminated comparisons but robust reflections of the underlying treatment effects.

Several caveats should temper interpretation. First, the five-year post-treatment horizon captures short- to medium-run adjustment but may understate long-run dynamics such as capital turnover, induced innovation, or labor market reallocation. Second, although effective tax rates and emissions factors are carefully constructed, measurement error and aggregation may obscure heterogeneity across sectors and households. Third, the analysis abstracts from distributional outcomes, which are politically salient even if aggregate GDP is unaffected. Finally, the external validity of these results to non-OECD settings remains uncertain, given differences in institutional capacity, energy structures, and enforcement.

Notwithstanding these limitations, the results provide compelling evidence that price-based instruments can play a central role in climate and energy policy. They show that substantive ETRs deliver meaningful reductions in fossil energy use and carbon intensity, accelerate renewable uptake, and do so without harming economic performance in the short run. Revenue recycling can further reinforce environmental gains and enhance acceptability. Together, these findings align with the journal's emphasis on empirically grounded, policy-relevant energy economics and contribute to the literature on efficient, equitable, and politically durable climate policy instruments.

The empirical findings from this investigation strongly support the environmental dividend effects, component of the Environmental Tax Reform (ETR) hypothesis and, crucially, fail to reject the weak form of the double-dividend hypothesis across OECD nations. Within five years of implementation, substantive ETRs were found to reduce per-capita energy use by 6–9 percent and lower energy intensity by 5–6 percent, simultaneously increasing the share of renewable energy in the total primary energy supply by 3–4 percentage points (Domingues. 2009). Consistent with the double-dividend theory, no statistically significant negative effect on GDP per capita was observed (Domingues, 2012).

These results are largely corroborated by the latest wave of academic research (2021–2025), which has increasingly focused on establishing causal or long-run links between fiscal policy and environmental outcomes. For instance, the finding that ETRs reduce overall energy consumption and energy intensity aligns with the long-run evidence presented by contemporary studies using alternative econometric techniques, such as the DOLS and FMOLS methods applied to OECD data, which also observed a negative effect on energy consumption and intensity (Dimitriades, 2023; Öner & Çetin, 2023). Furthermore, the quantitative impact is contextualised by studies suggesting that carbon price increases, a core component of ETR, lead to measurable reductions in carbon dioxide emissions, reinforcing the implied price-driven conservation effect observed herein (Kohlscheen, Laverde & Rungcharoen, 2024).

Regarding the substitution effect, our finding that the renewable share increases by 3–4 percentage points finds strong support in recent quantile regression analyses. For instance, Purohit and Baxi (2025) noted a distinctly asymmetric effect, where environmental tax effort raised the renewable share by up to 4.6 percentage points in the most responsive, high-adopting G-20 economies, a magnitude entirely consistent with the upper bound of our causal estimates (Purohit & Baxi, 2025). This consistency confirms that price signals generated by ETRs are an effective instrument for accelerating the transition to sustainable energy sources, a position widely accepted in the literature (e.g., Ikram, Zhou et al., 2023; Ikram, Ma et al., 2023; Zhang, Du & Zhang, 2023; Zhang, Fan & Li, 2023). The most significant contribution of the present study lies in its methodological

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approach, which addresses a key limitation in recent scholarship. While several recent papers have supported the positive environmental effects of environmental taxes (e.g., Ikram, Zhou et al., 2023; Ikram, Ma et al., 2023), others have yielded contradictory results, sometimes suggesting that environmental taxes could, paradoxically, stimulate emissions when tested using traditional, non-causal panel models (Leitão et al., 2025; Zhang, Du & Zhang, 2023; Zhang, Fan & Li, 2023). By employing a staggered difference-in-differences framework with Instrumental Variables (IV) and modern estimators (Callaway & Sant'Anna, 2021; Sun & Abraham, 2021), this research successfully navigates the endogeneity and treatment heterogeneity issues that plague conventional two-way fixed effects models. This robust causal identification confirms that the policies themselves—not unobserved pre-existing trends or policy selection—are the source of the observed environmental improvements.

Finally, the result that ETRs have no statistically significant negative effect on GDP per capita within the short-to-medium term (five years) strongly supports the feasibility of implementing green fiscal policies without measurable detrimental macroeconomic consequences. This finding aligns with the prevailing consensus on the weak double dividend in the short run (Domingues, 2017). While some recent studies using disaggregated tax revenues have suggested a statistically significant positive long-run effect on economic development in certain regions, such as the Nordic countries (Sveinsson, 2024), the primary finding of our study—that ETRs are not a burden on the economy—remains consistent across the OECD as a whole.

The causal evidence presented here on the efficacy of ETRs in driving energy conservation and substitution is largely validated by, and contributes substantially to, the latest empirical literature (2021–2025). By confirming the weak double dividend and providing robust estimates of the environmental gains, the study provides timely policy evidence for jurisdictions contemplating large-scale environmental fiscal reforms.

7. Future developments

This study can be complemented with a Modern staggered difference-in-differences. Countries adopt ETRs at different dates, so two-way fixed effects (TWFE) can deliver biased average treatment effects under heterogeneous dynamics due to non-convex weights from comparisons between early and late treated units. We therefore estimate cohort-specific event-study effects using (i) Sun–Abraham interaction-weighted estimators and (ii) Callaway–Sant'Anna (C&S) group-time ATTs. We report dynamic effects (event time kkk) relative to k=−1, average short-run effects (0–2 years), and medium-run effects (3–5 years). For transparency, we provide the Goodman–Bacon decomposition of the TWFE estimator to document the comparison weights. Standard errors are clustered at the country level; as a robustness check we report wild-cluster bootstrap p-values.
Estimating equations (sketch).

Let Yit be the outcome for country i in year t; Gi the cohort (ETR year); Dit=1[t≥Gi].

Sun–Abraham (IW event-study):

$$Y_{it} = \alpha_i + \gamma_t + \sum_{k \neq -1} \beta_k \, 1[t - G_i = k] \cdot 1[G_i \neq \varnothing] + \varepsilon_{it},$$

estimated with cohort-relative dummies interacted with cohort membership and appropriate "not-yet-treated" controls.

Callaway–Sant'Anna (group-time ATTs): Estimate ATT(g,t) for each cohort g vs. not-yet-treated in t; aggregate to dynamic effects k=t−g with appropriate weights. Researchers should diagnose bias with the Goodman-Bacon decomposition, report cohort-specific event studies, and assess robustness under alternative aggregation schemes. Using these modern estimators, coupled with transparent diagnostics, offers more reliable causal inference when treatment timing is staggered and effects are heterogeneous.

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Conclusions

This paper provides new causal evidence on the economic and environmental effects of environmental tax reform (ETR) in OECD countries. Using modern estimators for staggered adoption designs (Callaway & Sant'Anna, 2021; Sun & Abraham, 2021), we show that higher effective tax rates reduce energy consumption and energy intensity, increase the share of renewables, and do so without adverse short-run impacts on GDP per capita. These results are robust across specifications, cohorts, and revenue-recycling mechanisms, reinforcing their causal interpretation and credibility relative to conventional two-way fixed effects designs, which recent literature shows can be biased in heterogeneous treatment settings (Goodman-Bacon, 2021; de Chaisemartin & D'Haultfœuille, 2021; Roth, 2022).

The magnitudes are economically meaningful. A 20 percent increase in effective tax rates is associated with a 6–9 percent reduction in per-capita energy use, corresponding to demand elasticities between –0.30 and –0.45, values consistent with prior empirical studies of energy demand responsiveness (Metcalf, 2019). Translating these effects into avoided climate damages, our baseline calculation implies welfare gains of approximately 0.30 percent of GDP under a social cost of carbon (SCC) of USD 50 per ton of CO_2, with proportional scaling at higher or lower carbon price assumptions (Resources for the Future, 2021). Conservative sensitivity checks confirm that these gains persist across alternative parameterizations. Because the estimates exclude co-benefits such as improved air quality and health outcomes (OECD, 2019), they should be interpreted as lower bounds on the total welfare benefits.

These findings are consistent with the "double dividend" hypothesis (Goulder, 1995; Fullerton & Metcalf, 1998), showing that environmental improvements can be achieved without sacrificing short- to medium-run growth. Moreover, the analysis highlights the importance of revenue recycling: reforms that direct revenues to households or environmental investments modestly amplify renewable uptake and may enhance political durability, echoing evidence from the political economy literature (Carattini, Kallbekken, & Orlov, 2019; Parry, Black, & Roaf, 2022).

Limitations should temper interpretation. The five-year window captures short-run adjustment but not long-run dynamics such as capital turnover, induced innovation, or structural transformation. Aggregate measures of effective tax rates mask distributional effects that, while neutral in GDP terms, are crucial for policy feasibility. External validity to non-OECD economies may be limited given institutional and structural differences. Future work should extend the temporal horizon, integrate micro-level data, and embed causal estimates in dynamic general-equilibrium frameworks to capture innovation, equity, and intergenerational impacts.

Taken together, the results demonstrate that well-designed ETRs can achieve measurable reductions in fossil energy use and carbon intensity while preserving economic growth. They support the role of price-based instruments as efficient, welfare-enhancing, and politically viable pillars of climate and energy policy.

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THE PERCEPTION AND IMPACT OF GAMBLING AMONG COLLEGE STUDENTS IN SLOVAKIA*

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Abstract: Gambling behavior among college students is a complex phenomenon influenced by social environment, self-regulation skills, and the availability of online platforms. This article examines how students perceive the presence of gambling in their environment, assess their control over gambling, and associate the availability of online gambling with financial consequences. The research was conducted in the form of a quantitative electronic questionnaire survey among students of the Faculty of Management and Informatics at the University of Žilina (n = 202). The results showed that most students have experience with gambling in their social environment, most often through friends, classmates, or family. More than half of the respondents perceive their control over gambling as complete, one-third as partial, and a smaller proportion admitted to occasional loss of control. Most students consider online gambling to be easily accessible, but only a minority reported financial problems because of gambling. The findings suggest that subjective perceptions of the presence of gambling and the ability to regulate one's own behavior are key factors in predicting problem gambling, while the availability of online platforms alone does not necessarily lead to economic consequences. The integration of social, behavioral, and financial dimensions provides a new perspective on the formation of gambling behavior in young adults and identifies areas important for prevention and intervention.

Keywords: gambling; university students; self-control; addiction; social environment

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1. Introduction

Gambling is defined as risking something of value, most often money, on the outcome of an event with an uncertain outcome. Most individuals engage in gambling without serious negative consequences, but especially among young adults, gambling can quickly escalate into problematic forms (Lee et al., 2024). Global data confirm that 10.23% of university students experience gambling problems, causing personal, social, or financial difficulties, and another 6.13% meet the clinical criteria for gambling disorder (Nowak, 2018). These rates are significantly higher than those in the general population and represent a substantial public health concern. College students are particularly vulnerable because they are going through a period of life characterized by increasing independence, reduced parental supervision, intense peer influences, and increased availability of gambling opportunities, including online platforms. This environment has raised a generation that perceives

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gambling as a socially acceptable form of leisure activity, which may contribute to its normalization (Petry et al., 2017).

Excessive gambling has serious consequences in this population, as it is associated with financial difficulties and impaired mental and physical health (Oksanen et al., 2018; Armitage, 2021; Montiel et al., 2021). Gambling behavior exists on a continuum from mild to severe forms and is closely linked to substance use disorders, other behavioral addictions, and neurocognitive difficulties (Ford & Hakansson, 2020). Global estimates report a prevalence of problem gambling among adolescents and young adults ranging from 0.2% to 12.3%, with differences between countries reflecting the availability of gambling, the regulatory environment, and cultural attitudes (Calado et al., 2017).

In the context of gambling behavior among college students, a research gap persists, as existing knowledge focuses primarily on prevalence and individual risk factors, but pays limited attention to how students perceive gambling in their social environment, what beliefs they hold about their own control over gambling, and how they evaluate the availability of online gambling in relation to financial consequences. The aim of this article is therefore to comprehensively examine these three interrelated areas: the social environment, behavioral control, and the financial aspects of online gambling, thereby contributing to an understanding of the mechanisms that shape the gambling behavior of young adults. The novelty of the article lies in the integration of these three dimensions into a single analytical framework. The article examines how students reflect on the presence of gambling around them, how they assess their ability to regulate their gambling, and to what extent they associate the availability of online platforms with their own financial difficulties.

2. Theoretical background

2.1. Social environment and young adults' exposure to gambling

The social environment plays a crucial role in how college students perceive gambling and how often they engage in it. The motivation to earn money is one of the most significant reasons why young adults gamble (Song et al., 2024). More than 80% of first-year students consider financial security to be a key goal of their studies (Eagan et al., 2017), which may contribute to their openness to risky activities in their social environment. This age group also often exhibits higher impulsivity, which increases susceptibility to risky behavior, including gambling (Zolkwer et al., 2022; Shen, 2023).

College students engage in multiple forms of gambling, with lottery tickets and scratch cards often perceived as low-risk and easily accessible (Kam et al., 2017; Zhu, 2025). Sports betting is highly popular, especially among men, with a prevalence of up to 36.7% in some populations (Daniel et al., 2023). Informal betting among peers is also common, reflecting the social and community nature of gambling behavior in the student population.

Modern forms of gambling, particularly those associated with sports, including fantasy sports, also play a significant role. College students, and especially athletes, often engage in such activities (Marchica & Derevensky, 2016). Daily fantasy sports are particularly popular, and frequent participation in them is associated with increased gambling frequency and a higher risk of developing problematic behavior (Martin et al., 2018; McGivern & Mierzwinski, 2025). These findings point to the strong presence of gambling in the social groups and communities in which young adults move. Within these groups, members can also influence each other, which can lead to cooperative decision-making (Holubcik & Soviar, 2021; Blaskova et al., 2022; Holubcik et al., 2025). Young adults may thus make decisions influenced by their social group that they would not make independently.

However, the social aspects of gambling can also take on a negative form. Problem gambling disrupts interpersonal relationships, increases feelings of loneliness, frustration, and social dissatisfaction, which further predict the severity of gambling behavior (Floyd et al., 2025). The weakening of social support subsequently deepens isolation and stress, creating a cycle that encourages the continuation of problem gambling (Sherba & Gersper, 2017).

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Significant risk factors for young adults' exposure to gambling include young age, male gender, loneliness, and intense exposure to gambling advertising (Sirola et al., 2019; Riley et al., 2021; Freund et al., 2022; Sirola et al., 2023). Assessing and working with risk is challenging for these individuals (Koman et al., 2023). Family environment and socioeconomic status also play an important role. Lower socioeconomic status may lead to the perception of gambling as a form of coping with financial stress, while higher socioeconomic status may increase the frequency of recreational forms of gambling. Students with lower academic achievement are more likely to experience more serious psychological consequences of gambling (Livazovic & Bojcic, 2019). Individuals with lower incomes are also more likely to take out loans, which can place them under financial strain and subsequently contribute to the development of gambling disorder (Castren et al., 2018; Latvala et al., 2019; Hakansson, 2020).

Previous research shows that the social environment plays a significant role in shaping the gambling behavior of young adults, with a particular focus on motivation, popular forms of gambling, and risk factors such as age, gender, impulsiveness, and financial stress. These studies provide a good overview of the gambling activities students engage in, the social groups involved, and the influence of peers, family, and advertising. However, less is known about how students themselves subjectively perceive the presence of gambling in their immediate social environment and to what extent their experience with gambling varies depending on their age. It is precisely this limited knowledge about these perceptual and developmental differences that represents a research gap that this article seeks to fill.

2.2. Behavior control and self-regulation in gambling

Self-regulation and the ability to control behavior are key factors in understanding why gambling becomes a problem for some students. Although certain types of gambling allow players to use information to support their decision-making (e.g., sports statistics or card history), most gambling games are based on chance and probability, which systematically favors the operator. The result is mostly pure losses, which, although not a diagnostic criterion for gambling disorder, almost always accompany it in practice.

Behavioral control models show that psychological factors significantly influence the extent to which an individual can resist the urge to gamble. People with high levels of anxiety may use gambling to reduce tension or, conversely, experience increased stress when losing, which impairs their ability to make rational decisions. Gambling behavior should be viewed because of beliefs and attitudes related to money. Economic factors can play a significant role (Kusnirova et al., 2023; Kusnirova et al., 2024). Expectations of quick profits or financial security can, as with substance use, encourage the continuation of problematic behavior.

Impaired self-regulation is also closely linked to psychological difficulties. Problem gamblers often show increased levels of depression, anxiety, and suicidal thoughts (Liu et al., 2019; Potenza et al., 2019). These symptoms weaken the ability to control impulses, increasing the risk of losing control over gambling. Other factors include school stress and academic problems. Declining performance and lower participation in extracurricular activities can impair the ability to plan, organize time, and make thoughtful decisions, further increasing the risk of uncontrolled gambling (Benjet et al., 2023).

Control over gambling behavior is also influenced by a combination of multiple risk behaviors. Research confirms that problem gambling often overlaps with other behavioral addictions, such as compulsive use of the internet, social media, gaming, or excessive online shopping (Burleigh et al., 2019; Charzyńska et al., 2021; Muller et al., 2022; Tullett-Prado et al., 2023). Some authors even argue that these phenomena should be understood as forms of behavioral addiction (Brand et al., 2019).

At the same time, there is a strong bidirectional link between gambling and substance use. The occurrence of one risky behavior significantly increases the likelihood of the other (Caldeira et al., 2017; Buja et al., 2019; Castren et al., 2021). The combination of multiple problematic habits leads to impaired mental and physical health (Karlsson & Hakansson, 2018; Hakansson & Karlsson, 2020; Jolly et al., 2021) and creates a self-reinforcing cycle that prevents successful behavior control (Angioletti & Balconi, 2022; Carbonneau et al., 2023).

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Current research shows that self-regulation and control over gambling are key to understanding the transition from recreational to problem gambling. Psychological factors such as anxiety, depression, and academic demands have been found to weaken students' ability to plan, organize their time, and resist the urge to gamble. Problem gambling often overlaps with other risky and addictive behaviors, creating a cycle that makes it difficult to maintain control. Despite these findings, however, there is limited information on how students themselves perceive their ability to regulate gambling and how these perceptions are related to the frequency of gambling, which is a research gap that this article addresses.

2.3 The availability of online gambling and its financial consequences for students

Online gambling poses a specific risk to college students because it combines the high availability of digital platforms with the rapid dynamics of financial decisions. Up to two-thirds of sports bettors report a preference for the online environment over brick-and-mortar establishments, which significantly increases the frequency of gambling and accelerates financial losses (Daniel et al., 2023). This accessibility is one of the key mechanisms contributing to the development of problems and excessive gambling among young adults (Hollen et al., 2020; Riley et al., 2021; Emond et al., 2022).

The financial consequences of gambling are significant and closely linked to the diagnostic criteria for gambling disorders. Although losses alone are not sufficient to establish a diagnosis, they create a chain of personal, social, and psychological consequences. Students often perceive gambling as an opportunity to make money quickly, but most gambling games have a negative long-term return. Digitalization has contributed to the acceleration and intensification of these processes (Koman et al., 2022). This is one of the reasons why the online environment exacerbates this problem. Games are available 24/7, which allows for rapid accumulation of losses and subsequent financial problems, including the need to borrow money (Lostutter et al., 2019).

The high availability of online gambling is also associated with risky behavior patterns in groups of students who are more vulnerable to financial difficulties. Financial stress is particularly pronounced among low-income groups, where gambling can paradoxically function as a perceived "mechanism" for solving economic problems, but in practice leads to even greater indebtedness (Koomson et al., 2022). Polytechnic students, who are more likely to come from families with lower socioeconomic status, exhibit higher rates of risky behavior, including gambling, substance use, and less healthy lifestyles (Nori et al., 2021; Heiskala et al., 2021; Kataja et al., 2022; Ollila & Ruokolainen, 2022). This combination increases their vulnerability to the negative financial consequences of gambling and accelerates the transition from recreational gambling to problematic patterns.

Existing research emphasizes that the high availability of online gambling and its fast pace increase the risk of financial problems among students, with lower socioeconomic status and concurrent risk-taking behaviors further increasing vulnerability. Despite these findings, however, there is a research gap in how students perceive the availability of online platforms and how this perception relates to their experiences of financial difficulties, which our research seeks to address.

3. Research objective and methodology

The main objective of the research was to analyze the behavior and attitudes of university students towards gambling, identify factors influencing their level of involvement in gambling, and examine their perception of control over gambling and the possible financial consequences associated with this behavior. The research focused on determining how age, frequency of gambling, and perceived availability of online gambling influence students' experiences and attitudes.

A secondary objective was to determine the extent to which students are exposed to gambling in their social environment, how they perceive the risks and impacts of gambling behavior, and whether there is a demonstrable link between gambling frequency, perceived control, and the occurrence of financial problems.

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The results of the research should contribute to a better understanding of gambling behavior among young adults and can serve as a basis for proposals for preventive and educational measures aimed at reducing the risk of gambling addiction among university students, especially in Eastern Europe.

3.1. Description of the questionnaire survey

Research was conducted in the form of a quantitative questionnaire survey, the aim of which was to determine how gambling affects the behavior and financial decisions of university students, while also examining their perception of control over gambling and their attitudes toward the availability of online gambling.

The respondents to the questionnaire were students of the Faculty of Management and Informatics at the University of Žilina (Slovakia), where, according to official data, 1,517 students are enrolled. Based on estimates (Gambling Commission, 2024) that approximately 27% of young people aged 18-30 have personal experience with gambling, the target population of the research was narrowed down to approximately 410 potential respondents.

Questionnaire survey ran from December 12, 2024, to January 23, 2025. A total of 202 complete responses were obtained, which, according to Raosoft software calculations, represents a sufficiently representative sample with an acceptable selection error of 5% and a confidence level of 95%. The sample calculation is shown in the following table.

Table 1. Description of sample size according to Raosoft software

FACTOR	SIZE/PERCENTAGE
Acceptable margin of error	5%
Level of reliability	95%
Population size	410
Questionnaire completion rate	50%
Recommended sample size	199

Source: Own processing

An electronic questionnaire created using Google Forms was used to collect data. It was distributed via social networks (primarily Instagram and Facebook) and was also shared through the university's student communication channels, which made it possible to reach the target group of university students in an effective and inexpensive way.

The choice of electronic data collection was motivated by several advantages that this method offers. Electronic questionnaires allow for faster data processing and analysis, as responses are recorded immediately after submission and are available in digital form. Another significant advantage is the low cost of using online tools, such as Google Forms, which eliminates printing and distribution costs (Evans & Mathur, 2005). In addition, the electronic form guarantees the anonymity of respondents, which, according to Hunter (2012) increases the honesty of responses, especially in research on socially sensitive topics such as gambling behavior. Finally, online surveys allow for a geographically wider range of respondents and provide a convenient way to complete the questionnaire at a time and in an environment of the respondents' choosing.

Despite these advantages, this method also has certain limitations. The main disadvantage is a lower response rate, especially in cases where respondents do not have enough time or motivation to complete the questionnaire (Sue & Ritter, 2012). At the same time, selection bias may occur, as the survey primarily targets social media users who have access to the internet.

Questionnaire used contained 12 closed questions, which were divided into three thematic sections. The first section focused on basic demographic data; the gender and age category of respondents. The second section examined experience and behavior related to gambling, including frequency of play, degree of control over play, emotional reactions to winning, and the occurrence of financial problems. The third section was devoted to attitudes and perceptions of gambling, specifically the assessment of the availability of online gambling and the perception of the effectiveness of preventive measures. Questions were designed as closed questions,

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multiple-choice questions, and scale items using a Likert scale from 1 to 5, which allows for measuring the degree of agreement or disagreement with given statements.

3.2. Data processing and dependency analysis

The data obtained were processed using descriptive statistics, which enabled a basic analysis and overview of the structure of respondents' answers. Using percentages, averages, and graphical representations, it was possible to obtain an overview of the distribution of responses to individual questions and identify basic trends in student behavior in relation to gambling.

Inferential statistical methods were then applied to verify the relationships between variables, which made it possible to test the validity of the hypotheses. The χ^2 test of independence (chi-square test) was used to examine the relationship between age category, frequency of gambling, and sense of control over gambling. This test is suitable for analyzing relationships between categorical variables, allowing us to determine whether there is a statistically significant relationship between the two phenomena under study (Field, 2018).

Spearman's correlation analysis was used to examine the relationship between the perceived availability of online gambling and the occurrence of financial problems. This non-parametric correlation coefficient allows us to assess the strength and direction of a monotonic relationship between two variables expressed on an ordinal scale, for example, between the degree of agreement with a scale question and the assessment of the frequency of financial problems (Dancey & Reidy, 2007). This approach, combining descriptive and inferential statistics, allowed not only for a quantitative evaluation of the responses, but also for verification of the existence of significant relationships between the variables under investigation.

3.3. Hypotheses and research questions

Based on the research objectives, three hypotheses were formulated, which build on theoretical foundations and focus on identifying relationships between selected variables related to gambling behavior among university students. Each hypothesis is supplemented by corresponding research questions that further specify the direction of the study and allow for a more accurate understanding of the attitudes, behaviors, and experiences of respondents in gambling.

The first hypothesis focuses on the relationship between the age of students and their experience with gambling addiction in their environment. The second hypothesis examines the relationship between the frequency of gambling and the degree of subjectively perceived control over this behavior. The third hypothesis addresses the relationship between the perceived availability of online gambling and the occurrence of financial problems among students. Table 2 below provides an overview of all the hypotheses formulated, together with the relevant research questions.

Table 2. Formulation of hypotheses and corresponding research questions

Hypothesis	Research Questions (RQ)
H1: Younger university students are more likely to encounter gambling addiction than older ones.	**RQ1a:** Does the age of students influence the likelihood of encountering gambling addiction in their surroundings? **RQ1b:** How do students perceive the presence of gambling within their social environment (family, friends, classmates)?
H2: The more frequently university students engage in gambling, the lower the perceived level of control over their gambling behavior.	**RQ2a:** Is there a relationship between the frequency of gambling and the perceived control over gambling behavior? **RQ2b:** How do students subjectively assess their ability to control gambling (e.g., "I have full control" vs. "I sometimes lose control")?
H3: Students who consider online gambling easily accessible are more likely to report financial problems.	**RQ3a:** Is there a relationship between the perceived accessibility of online gambling and the occurrence of financial problems among students? **RQ3b:** How often do students experience financial difficulties because of gambling (e.g., needing to borrow money)?

Source: Own processing

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4. Results

The results are organized according to individual areas of the questionnaire and follow on from the research questions formulated. First, the demographic data of the respondents are presented, which allows us to describe the composition of the research sample. This is followed by an analysis of experiences with gambling addiction, frequency of gambling, perception of control over gambling, and the occurrence of financial consequences. The final part of this chapter focuses on statistical verification of dependencies between variables using the chi-square test of independence and Spearman's correlation.

Results obtained are interpreted in relation to the formulated hypotheses and supplemented with graphical and tabular representations. This approach allows for a more comprehensive understanding of students' behavior patterns and the factors that influence their relationship to gambling.

Basic characteristics of the research sample
The research sample consisted of 202 respondents, of whom 54% were men (n = 109) and 46% were women (n = 93). The gender ratio is therefore relatively balanced, which allows for a more objective comparison of responses between the two groups.

In terms of age structure, the most numerous groups of respondents were aged 18–30 (three separate categories of age in this range), accounting for 94.1% of all research participants (n = 190). Respondents under the age of 18 (3.5%, n = 7) and those aged 31–40 (2%, n = 4) were less represented, and only 0.5% of respondents reported being over 51 years of age (n = 1). Most respondents therefore fall into the category of young adults, typical university age, which confirms the suitability of selecting this group for studying topics related to gambling behavior and its impacts.

Experience with gambling addiction
When asked whether they had ever encountered gambling addiction – either in themselves, their loved ones, or someone in their environment – 59.9% of respondents answered affirmatively (n = 121). The remaining 40.1% of students (n = 81) stated that they had not encountered this phenomenon before.

These results indicate that gambling addiction is not an unknown phenomenon among university students, and more than half of those surveyed have personal or indirect experience with its occurrence in their social environment. This data confirms that the issue of gambling also affects the younger population and may be present in the everyday lives of students, whether through classmates, friends, or family members.

Table 3. Respondents' experience with gambling addiction

Answer	Number of respondents (n)	Percentage representation (%)
Yes – I have encountered addiction (in myself, loved ones, or acquaintances)	**121**	**59,9**
No – I have not encountered addiction	**81**	**40,1**

Source: Own processing

In line with hypothesis H1, we then examined whether there is a correlation between the age of respondents and their experience with gambling addiction. To verify this correlation, we applied the χ^2 test of independence, the results of which did not show a statistically significant correlation ($p = 0.2399$). Based on this, it can be concluded that the age of respondents does not have a significant impact on the likelihood that they have encountered gambling addiction. This result suggests that experience with addiction occurs across age categories of students without significant differences.

Frequency of play and control over play
Another part of the research focused on determining how often university students gamble and what level of control over gambling they perceive themselves to have. Results showed that most respondents (68.8%) do not

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gamble at all, while 21.3% gamble only occasionally (e.g., several times a year) and 9.9% gamble regularly (weekly or monthly). These data suggest that gambling behavior does occur among students, but for most it is irregular and recreational in nature.

In terms of perceived control over gambling, 57% of respondents said they had complete control over their gambling, 31% said they had only partial control, and 12% admitted that they sometimes lost control. These results suggest that a small but significant proportion of players are aware of the risk of losing control over their gaming, which may be an early sign of problematic behavior.

Table 4. Respondents' frequency of gambling and perception of control over gambling

Variable	Response category	Number (n)	Percentages (%)
Frequency of play	I don't play at all	139	68,8
	Occasionally (several times a year)	43	21,3
	Regularly (monthly to weekly)	20	9,9
Feeling of control over gaming	I have complete control	115	57
	I have only partial control	63	31
	Sometimes I lose control	24	12

Source: Own processing

To verify the relationship between gaming frequency and sense of control, a χ^2 independence test was used, which confirmed a statistically significant dependence between the variables under study ($p < 0.001$). The test result supports the formulated hypothesis H2, according to which the more frequently university students gamble, the lower the degree of control over gambling they report.

Online gambling and financial problems

The last part of the research focused on the perception of the availability of online gambling and its possible financial consequences among university students. The aim was to find out whether students who consider online gambling to be easily accessible also admit to financial problems because of gambling more often.

Nevertheless, only 16.3% of respondents reported that they had experienced financial difficulties because of gambling, such as having to borrow money or cut back on personal expenses. The remaining 83.7% of respondents did not report such problems, suggesting that most gamblers engage in gambling to a relatively controlled extent and with low economic impact.

Table 5. Respondents' perceived availability of online gambling and financial consequences of gambling

Variable	Response category	Number (n)	Percentages (%)
Perceived availability of online gambling	Very easily accessible	87	43,1
	Rather easily accessible	62	30,7
	Rather difficult to access	39	19,3
	Very difficult to access	14	6,9
Financial problems due to gambling	Yes, sometimes	33	16,3
	No, never	169	83,7

Source: Own processing

Spearman's correlation was used to verify the relationship between the perceived availability of online gambling and the occurrence of financial problems. The test result did not show a statistically significant relationship between the variables under study ($p = 1.000$), thus rejecting hypothesis H3. This result suggests that even though students perceive online gambling as highly accessible, this factor does not have a direct impact on their financial situation.

This finding can be explained by the fact that students in the sample do not generally gamble regularly or invest large sums of money, which reduces the likelihood of financial problems arising. Similarly, research by Nsereko

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et al. (2023) points out that among students who gamble only occasionally, serious economic consequences occur only in exceptional cases.

Verification of hypotheses and research questions

Based on the results of the quantitative survey, three research hypotheses were verified, which were linked to the research objectives and focused thematically on the age of students, frequency of play, sense of control, and financial consequences of online gambling. Each hypothesis was supplemented by two research questions (RQ) that allowed for a deeper understanding of the attitudes and experiences of the respondents.

The aim of the first hypothesis was to verify whether the age of students influences the likelihood that they have encountered gambling addiction. The answer to RQ1 showed that age category has no statistically significant influence ($p = 0.2399$). Students in all age groups reported a similar level of exposure to addiction, a total of 59.9% of respondents had encountered this phenomenon, indicating a high prevalence of gambling in their environment regardless of age.

The answer to RQ1b confirms that gambling is perceived primarily as part of the social environment. Respondents reported that they most often encountered gambling through friends (41%), classmates (27%), or family (19%). These findings suggest that gambling behavior is socially visible and normalized in the university environment but not necessarily linked to a specific age group.

The second hypothesis examined whether there is a relationship between the frequency of gambling and the perception of control over gambling. The answer to RQ2 showed a statistically significant dependence ($p < 0.001$), confirming hypothesis H_2. Students who gamble more frequently (9.9% regularly; 21.3% occasionally) reported a lower sense of control over their behavior. Conversely, those who do not gamble mostly declared that they could easily control their gambling.

The third hypothesis focused on the relationship between the perceived availability of online gambling and the occurrence of financial problems. The results showed that there is no statistically significant relationship between these variables ($p = 1.000$), and therefore H_3 was rejected.

The answer to RQ3 indicated that up to 73.8% of students consider online gambling to be easily accessible, but this factor has no direct impact on the occurrence of financial problems. Only 16.3% of students responded to RQ3b that they had experienced financial difficulties (e.g., needing to borrow money or cut back on spending) because of gambling. These results suggest that although online gambling is perceived as very accessible, most students engage in it recreationally, without significant economic consequences. Based on the presented results, the individual hypotheses and research questions can be evaluated as follows:

Table 6. Verification of research hypotheses and answers to research questions

Research question (RQ)	Hypothesis (H)	Variables	Expected relationship	Statistical test	Result	Conclusion
RQ1a: Does the age of students influence the likelihood of encountering gambling addiction in their surroundings?	**H1:** Younger university students are more likely to encounter gambling addiction than older ones.	Age ↔ Experience with addiction	Weak positive correlation	chi-square of independence	$p = 0.2399$	Rejected
RQ1b: How do students perceive the presence of gambling within their social environment (family, friends, classmates)?						
RQ2a: Is there a relationship between the frequency of gambling and the perceived control over gambling behavior?	**H2:** The more frequently university students engage in gambling, the lower the perceived level of	Frequency of play ↔ Sense of control	Negative dependency	chi-square of independence	$p < 0.001$	Confirmed

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RQ2b: How do students subjectively assess their ability to control gambling (e.g., "I have full control" vs. "I sometimes lose control")?	control over their gambling behavior.					
RQ3a: Is there a relationship between the perceived accessibility of online gambling and the occurrence of financial problems among students? **RQ3b:** How often do students experience financial difficulties because of gambling (e.g., needing to borrow money)?	**H3:** Students who consider online gambling easily accessible are more likely to report financial problems.	Online availability ↔ Financial problems	Weak positive correlation	Spearman's correlation	p = 1.000	Rejected

Source: Own processing

5. Discussion

In the context of gambling behavior among college students, there remains a research gap, as existing knowledge focuses primarily on prevalence and individual risk factors, but pays limited attention to how students perceive gambling in their social environment, what beliefs they hold about their own control over gambling, and how they evaluate the availability of online gambling in relation to financial consequences. The aim of this article is therefore to comprehensively examine these three interrelated areas: the social environment, behavioral control, and financial aspects of online gambling, and thus contribute to understanding the mechanisms that shape the gambling behavior of young adults. The novelty of the article lies in the integration of these three dimensions into a unified analytical framework.

The research was conducted in the form of a quantitative electronic questionnaire survey among students of the Faculty of Management and Informatics at the University of Žilina (n = 202). Data were collected online through social networks and university communication channels, which enabled effective and anonymous information gathering. The data analysis combined descriptive statistics and testing of dependencies between variables, which made it possible to identify patterns of behavior and connections between the perception of gambling, control of gambling, and financial consequences.

Our results show that most students had experience with gambling in their social environment, most often through friends, classmates, or family. A comparison with foreign studies (Zolkwer et al., 2022; Palomäki et al., 2025) shows that the level of students' contact with gambling is comparable to international trends, with young adults increasingly exposed to the influence of gambling, especially in the online environment. These findings confirm the importance of the social environment in shaping gambling behavior and expand our knowledge of motivations, the popularity of various forms of gambling, and the influence of peers, family, and advertising (Eagan et al., 2017; Zolkwer et al., 2022; Shen, 2023).

Sports, especially sports betting and fantasy sports, which are highly popular among students and especially among men, play a special role in the gambling behavior of young adults (Marchica & Derevensky, 2016; Martin et al., 2018; Daniel et al., 2023). Digitalization also reinforces this trend, as most bettors prefer the online environment, which increases the frequency of gambling and accelerates financial losses. The results of our research support this picture. Students perceive online gambling as very accessible, often encountering it in their social environment, and although most gamble recreationally, some of them admit to reduced control and financial difficulties. This suggests that the sports and online environments significantly increase the risk for a smaller but vulnerable group of students.

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In the area of behavior control and self-regulation, we found that more than half of the students perceive their control over gambling as complete, about one-third as partial, and a smaller proportion admitted to occasional loss of control. These results are consistent with the theory of behavioral addictions, according to which subjective control decreases with increasing frequency of gambling (Allen et al., 2025; Kapukotuwa et al., 2025), and support the assumptions of models that emphasize the role of psychological factors such as anxiety, depression, or a combination of risk behaviors in increasing the likelihood of transitioning from recreational to problem gambling (Liu et al., 2019; Potenza et al., 2019; Burleigh et al., 2019; Charzyńska et al., 2021; Muller et al., 2022; Kurilla, 2022; Benjet et al., 2023).

In terms of the availability of online gambling and its financial consequences, most students consider online gambling to be very accessible, which corresponds with the findings of foreign studies (Zolkwer et al., 2022; Suria Martinez et al., 2024), which point out that digital platforms allow easy access to gambling without physical or age restrictions. Nevertheless, only a minority of students reported having financial problems because of gambling, suggesting that high accessibility alone may not lead to economic hardship if gambling is predominantly recreational (Hollen et al., 2020; Riley et al., 2021; Emond et al., 2022; Koomson et al., 2022; Daniel et al., 2023).

These findings integrate three dimensions of gambling behavior: social environment, behavioral control, and online gambling availability, and contribute to a better understanding of the mechanisms that influence students' gambling decisions. The results suggest that subjective perceptions of the presence of gambling and self-control are more important for predicting problem behavior than the availability of online platforms alone, providing valuable information for prevention and intervention among young adults (Castren et al., 2018; Latvala et al., 2019; Livazovic & Bojcic, 2019; Hakansson, 2020).

Research has confirmed that students' gambling behavior is closely linked to their social environment and psychological self-regulation mechanisms. Subjective perceptions of control over gambling decrease with increasing frequency of gambling, while high availability of online platforms does not in itself predetermine the emergence of financial problems. The integration of social, behavioral, and financial dimensions provides a new perspective on the formation of gambling behavior in young adults and identifies areas that are key for prevention and intervention.

Overall, the findings of the authors are like previous international insights, particularly regarding the influence of the social environment, subjective perceptions of control, and psychological factors contributing to gambling behavior. However, certain aspects differ, especially the absence of a clear link between perceived accessibility of online gambling and financial harm, which contrasts with some earlier studies. These differences highlight the importance of contextual, cultural, and behavioral specifics within the Slovak student population.

Conclusions

The research results underscore the importance of a comprehensive view of students' gambling behavior that integrates social, behavioral, and financial factors. The article provides new insights into how gambling is formed in the environment of young adults and what role subjective perceptions of control and social stimuli play. This approach is particularly important in an era of rapid digitalization, when mobile apps, online casinos, and sports betting available 24/7 are significantly changing behavior patterns, lowering barriers to entry, and reinforcing impulsive decision-making. The findings can thus be used to develop prevention programs for the academic environment and broaden youth communities, including sports students and active athletes, who are more likely to engage in sports-related forms of gambling, such as sports betting and fantasy sports.

To remind readers of the key empirical outcomes, the study confirmed Hypothesis H2, demonstrating that more frequent gambling among university students is associated with a lower perceived level of behavioral control. In contrast, Hypothesis H1 was rejected, as age did not significantly influence the likelihood of encountering gambling addiction in one's surroundings, and Hypothesis H3 was also rejected, indicating no statistically significant relationship between the perceived accessibility of online gambling and the occurrence of financial problems.

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The novelty of this research lies in its integrated analytical perspective, combining social-environmental exposure, self-regulation dynamics, and financial consequences within a single framework. This holistic approach offers a more complete understanding of how gambling behavior develops among young adults in the digital era. The practical value of the findings is reflected in their potential to inform prevention strategies, university counselling services, and targeted interventions aimed at strengthening students' behavioral control and awareness of gambling risks.

The research has several methodological limitations that need to be considered. First, the sample was selected from a single faculty, which limits the possibility of generalizing the results to the entire population of university students. In addition, the faculty's focus on management and information technology may lead to a bias in the results toward online platforms. Second, data collection was conducted electronically, which may lead to selection bias. It primarily targets active users of social networks and digital platforms, who may differ in their approach to gambling. Third, the self-assessment items used may not accurately capture actual behavior, especially on topics that respondents may perceive as sensitive or stigmatized.

Future research should expand the sample to include students from different universities and study programs, including sports disciplines, where the link to sports betting and informal betting is more pronounced. An in-depth qualitative analysis would also be welcome, as it would allow for a more accurate capture of the motives, emotional aspects, and social dynamics associated with gambling. Given the increasing digitalization, it is also appropriate to examine new forms of online gambling: sports betting via mobile applications, instant betting, daily fantasy sports, and gamified platforms, which represent a growing part of the market and have a significant impact on young adults.

At the same time, it would be beneficial to monitor how perceptions of control, frequency of play, and financial consequences change over time, especially as students transition to the labor market or organized sports. These findings could help in the development of targeted prevention measures that respond to digital trends and the specifics of the sports environment.

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TOWARDS MORE SUSTAINABLE PRODUCT DESIGN THROUGH CONSUMER EXPERIENCE

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Abstract. It is known from various studies that the choice of the drinkware could deeply affect consumer perception during beverage consumption. In our previous study we have demonstrated that there are a lot of differences in the ratings of taste, palatability bitterness and saturation were noted depending on the type of vessel in which beer was served. This study continues our previous research and expands it even further. In this study we test four different types of beer – each one with a different essence content. This is to determine whether glassware type affects customer experience from drinking each type of beer. Four types of beer purchased from different producers were used for the research. Beer samples for evaluation were served in beer mugs with a classic design and solid construction, tall glasses (wheatbeerglasses) with a characteristic elongated shape, and beer goblets (also called tulip glass), distinguished by a short stem and a very large bowl that tapers towards the top. The experimental results showed how the characteristics of a glass could affect beverage bouquet and flavour, and suggest that their rational optimization, based on experimental data, could enhance the consumer enjoyment of it. Taking into account the above studies, certain conclusions can be drawn regarding the research we conducted. Light beer with an essence content 12% served in a tulip glass has been assessed worse in every single tested trait. Odour, taste, saturation, palatability, bitterness and general quality index (GQI) have been perceived worst when the beer was served in tulip glass. It seems that tulip glass is particularly unsuitable for this type of beer. Moreover, sustainability considerations are becoming increasingly relevant in this context. Understanding the interactions between the drink and its container may foster more deliberate and responsible purchasing behavior. The above-mentioned factors also affect the consumer experience that can be created by combining a drink with the right glass.

Keywords: beer quality; glass quality; sensory evaluation; sustainability; design; glass-beverage interactions; consumer experience

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1. Introduction and review of literature

Drinking and eating is a multisensory experience, and the appearance of a beverage can shape our expectations (Van Doorn et al., 2019). Beer is one of the most consumed beverages, representing 78% of alcoholic beverages worldwide (Gonzalez Viejo et al., 2022). People generally associate beer with alcohol with positive emotions (Sandilya et al., 2023). Due to its popularity, growing demand and availability of new technologies and materials, the beer industry has become a highly competitive market where improvement and innovation have become necessary. Historically, vessels have been looked upon solely as a device to transfer beverage from container to mouth, and design has not focused upon scientific principles (Manska, 2018). Today different ideas have been created in the beer industry to improve consumer's experience. Some of them include cross-industry strategies like serving beer in certain type of glassware. Packaging and the type of glass used for consumption can be a key factor influencing the customer experience (Hernández-Mora et al., 2022) (Gonzalez Viejo et al.,

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2022). Glass has been a preferred packaging material for decades, and its role in the brewing industry is crucial. It has a positive impact on the quality of beer and is also preferred for ecological reasons (Nieto-Villegas et al., 2024). Glass vessels (like beer mugs, tulip glasses etc.) are also most popular when it comes to beer consumption. New drinking vessel concepts are initiated by glassware and beverage companies to increase sales or create a perceived style identity for a particular beverage (Manska, 2018). Previous studies have shown that consumers maintain that beer in glass bottles has a better aroma and taste than beer in cans, confirming how packaging can have a psychological impact on consumer perceptions of product quality (Elzinga et al., 2015) (Merlino et al., 2020).

Several studies have found that the magnitude of user satisfaction is associated with a user's amount of experience with the product or system under evaluation (Borsci et al., 2015) (McLellan et al., 2012) (Lindgaard & Dudek, 2003). Numerous studies have been conducted on how consumers perceive the sensory characteristics of beer in various situations. (Blackmore et al., 2022) examined how sensory and hedonic expectations shape perceived properties of regular and non-alcoholic beer. They demonstrated that product-related cues can significantly influence consumer's perception of taste, flavour and mouthfeel and that these effects are mediated by expectations. (Nieto-Villegas et al., 2024) tested consumer expectations towards craft and industrial beers, and eco-friendliness of beer's packaging. They report that beer consumers have an unfavourable perception of aluminium cans and more favorable towards glass. Yang & Raghubir (2005) tested how consumer expectations influence perceived quality of beer packaging (glass bottles and metal cans). They suggest that the differential purchase quantities for bottles and cans are contingent on the context for which beer is being purchased. The study conducted by (Sandilya et al., 2023) revealed that the texture of the glass affected liking in a non-alcoholic beer sample. They used four different containers with distinct textures, named Plain, Bubbly, Prickly, and Ceramic, to evaluate their impact on the sensory properties of two beer samples. They also found out, that using a ceramic vessel with a different visual appearance than the other three glasses did not significantly affect the perception of the sensory attributes of the samples. In the study conducted by (Ribeiro et al., 2021) respondents were asked about their impressions and expectations regarding five craft beers of different colors, served in seven beer glasses. They discovered that color of craft beers influenced the expectations of consumers and experts, so that craft beer with similar colors was associated with the same glass shape. It was concluded that the beer glass shape could directly influence the consumer expectancy on craft beers. Other researchers have found that the right glass can increase or decrease alcohol consumption, depending on its shape (Troy et al., 2015).

The preceding literature review demonstrates that a wide range of factors can influence how sensory impressions are evaluated. Continuous innovation in glassware design has resulted in an expanding diversity of forms intended to complement traditional styles. However, this abundance of shapes and types of drinking vessels can also create uncertainty among consumers when selecting the most suitable option. Scholars further note that it remains unclear whether findings regarding the impact of glass shape on the perception of wine's organoleptic characteristics can be generalized to other, less complex beverages such as soft drinks, beer, or mixed drinks (Spence & Doorn, 2017).

Given these uncertainties, further investigation into how the form of a glass vessel influences the sensory and psychological experiences associated with consuming different types of beverages appears well justified. The outcomes of such research could be beneficial not only for consumers, by guiding more informed purchasing decisions, but also for manufacturers, who may use this knowledge to refine product design and marketing strategies. The product has a combination of tangible and intangible attributes offered by firms for purchase. (Lin & Cheng, 2017) Shape, visual appearance and weight can be mentioned among many tangible attributes. (Chien et al., 2016) Subjective consumer experiences resulting from interactions with other products are intangible attributes.

Results revealed five primary factors contributing to meaning-making and value creation – consumer requirements; simplicity; the context of user behavior, preferences, and experiences; elements determining the perceived product quality; and traditional culture (Bin Ali et al., 2025). All of these factors can be applied to the design of glassware to achieve the best interactions between the product and the beverage.

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Moreover, sustainability considerations are becoming increasingly relevant in this context. Understanding the interactions between the drink and its container may foster more deliberate and responsible purchasing behavior. As previous studies have shown, consumers' perceptions of beverage quality significantly affect their product-related choices (Mehta et al., 2022). Consequently, when consumers select glassware that aligns more closely with their actual needs, they simultaneously contribute to a reduction in the consumption of natural resources and support more sustainable patterns of consumption.

It has long been known that our representations and beliefs influence our daily decisions, especially in consumption. Therefore, to better understand consumer behaviour towards a given product, it is crucial to know how it is represented (Sester et al., 2013) (Hernández-Mora et al., 2022).

Certain expectations may also result from the associations that users have with different types of glass. In our previous study we have demonstrated that there are a lot of differences in the ratings of taste, palatability bitterness and saturation were noted depending on the type of vessel in which beer was served. (Dubis & Baran, 2025) This study continues our previous research and expands it even further. In this study we test four different types of beer – each one with a different essence content. This is to determine whether glassware type affects customer experience from drinking each type of beer.

2. Materials and methods

Four types of beer purchased from different producers were used for the research:
- light beer with essence content 12%,
- light beer with essence content 14%,
- dark beer with essence content 11,9%
- porter beer with essence content 20%

Beer samples for evaluation were served in beer mugs with a classic design and solid construction, tall glasses (wheatbeerglasses) with a characteristic elongated shape, and beer goblets (also called tulip glass), distinguished by a short stem and a very large bowl that tapers towards the top. The mugs are used for beers such as lager. IPAs, for example, are served in mugs whose shape helps bring out the full flavor of the beer. Tall glasses were designed for wheat beers. The appearance of the glass used in the study is shown in Photo 1 below.



Photo 1. Glassware used in the study. Beer mug (left), tall glass (center), tulip glass (right)
Source: own photography

In this paper qualitative studies have been used. This type of studies collects information from various stories and experiences to understand the link between consumer and product. The study of how ideas, events or objects are represented in language and how they make sense to people, as well as the elements that influence thoughts, feelings and behaviour of people, have been investigated with qualitative approaches (Hernández-Mora et al., 2022). There are a number of standards designed to ensure that a qualitative approach produces objective and high-quality results. In this study (*PN-ISO 6658:1998 Analiza sensoryczna. Metodologia. Wytyczne ogólne*), (*PN-ISO 4121:1998 Analiza sensoryczna. Metodologia. Ocena produktów żywnościowych przy użyciu metod skalowania*) and (*PN-A-79095 Piwo - Pobieranie i przygotowywanie próbek*) standards were used to ensure accuracy and repeatability of results. The sensory evaluation of the beer was performed by a trained 10-person

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team with appropriate, verified sensory sensitivity. The most important participant characteristic is that the participant is representative of the population of end users to whom the administrator wants to generalize the results of the test (Lewis & Sauro, 2021). So all the evaluators declared, that they are beer consumers. The beer samples were assessed in three sessions. In each session beer were served in different type of the container. In the first session, beer samples were poured into mugs, in the second into tall glasses and in the third into tulip glass. In each session, each assessor assessed nine beer samples. The assessment was aimed at determining the level of organoleptic characteristics of beer (odour, taste, palatability, saturation and bitterness) using a 6-point scale according to PN-ISO 4121:1998 and determining on this basis the overall quality of the assessed beer types. Each point of the scale corresponded to a clear definition of quality. The scale included 6 quality levels of the assessed parameters:
High quality - very good - 6 points; good - 5 points.
Acceptable quality - average - 4 points; poor - 3 points.
Low quality - very poor - 2 points; bad - 1 point.

After each session, a General Quality Indicator was calculated for each type of beer using the following formula:
$GQI = \Sigma C_i * W_i$, in which:
GQI – General Quality Indicator
C_i – evaluation of the consecutive sensory features;
W_i – weighting coefficient of the consecutive sensory feature (smell – 4, taste – 8, palatability – 12, saturation – 2, bitterness – 4). The weighting coefficients were adopted according to Annex D of PN-A 79093-1-2000-P.

The results were statistically analyzed using Statistica 13.3 software. The following methods were used in the analysis:
- calculation of basic statistical measures – arithmetic mean (M) and standard deviation (Sd);
- one-way analysis of variance – Fisher-Snedecor parametric F test combined with post-hoc analysis, in which the least significant difference (NIR) test was used. These tests were used to examine the degree of differentiation of assessments between individual experts;
- Kruskal-Wallis nonparametric test for a one-way system. This test was used to examine the differentiation of assessment results depending on the type of beer and the type of vessel. In the case of rejecting the null hypothesis, an additional post-hoc analysis was performed using Dunn's multiple comparisons test with Bonferroni correction.

Verification of all hypotheses was performed at the significance level of $\alpha = 0,05$ based on the test probability value "p". It was assumed that $p \leq 0,05$ It was assumed that $p \leq 0.05$ indicates significant differentiation of the dependent variable depending on the category of the qualitative factor (Stanisz, 2006).

3. Results

The results of the organoleptic quality assessment (GQI; mean and standard deviation values) of the tested beers performed by individual experts are presented in Table 1.

Table 1. Results of organoleptic quality assessment (GQI) of the tested beers

Evaluator no.	Mean	Standard deviation
1	4,81	0,40
2	3,86	0,68
3	4,86	0,69
4	5,18	0,82
5	4,68	0,74
6	4,32	0,67
7	4,31	0,68
8	4,77	0,63
9	4,83	0,79
10	4,50	0,88

Source: own study

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Test F showed that the average GQI score scores of all beers combined vary depending on the person performing the assessment (Table 1). The NIR test showed that the No. 2 and No. 4 evaluators were particularly different from the team. Therefore, further analysis of the results was performed for a team of 8 people, omitting evaluators no. 2 and 4.

The results of the organoleptic quality assessment of all beer samples evaluated in different vessels are presented in Table (mean values for eight evaluators). The nonparametric Kruskal-Wallis test showed significant differences in organoleptic quality. The test probability value "p" is 0.047. A post-hoc analysis of Dunn's test showed that the highest quality level was assessed for light beer with an essence content 14%, and the lowest level was assessed for the organoleptic quality of light beer with 12% essence.

Table 2. Results of organoleptic quality assessment (GQI) of various types of beer

Beer type	mean
light beer with an essence content 12 %	4,51
light beer with an essence content 14%	4,98
dark beer with an essence content 11,9%	4,69
porter beer with an essence content 20%	4,75

Source: own study

There are also significant differences between the quality of beer served in a different vesels. Post-hoc analysis using Dunn's test showed that beer served in a tulip glass was rated lower than beer served in a mug and a glass (Table 3).

Table 3. Results of the organoleptic quality assessment (WJC) of all types of beer evaluated in different vessels

Glass type	mean
beermug	4,90
tulip glass	4,45
glass	4,73

Source: own study

The results of the organoleptic quality of different beer types served in different vessels are presented in Table 4. The Kruskal-Wallis test demonstrated a significant effect of vessel type on the organoleptic quality of light beer with an essence content of less than 13% and dark beer ($p < 0.05$). Post-hoc analysis using Dunn's test revealed that:

- the average quality level of light beer up to 13% essence is lower when served in a glass than when served in a tulip glass or beermug.
- the average quality level of dark beer is lower when served in a glass than when served in a tulip glass or beermug.

Table 4. Results of the organoleptic quality assessment of individual beer types served in different vessels (The same letter symbols next to the mean values indicate that there is no difference between them in Dunn's test)

	light beer with essence content 12%	light beer with essence content 14%	dark beer with essence content 11,9%	porter beer with essence content 20%
beermug	4,83b	4,92	5,01b	4,97
tulip glass	4,07a	5,03	4,84b	4,62
glass	4,63b	5,00	4,23a	4,67
	p value			
	0,001	0,907	0,029	0,556

Source: own study

The results summarized in Table 4 are also presented in Figure 1. At a significance level of 0.05, it can be concluded that the type of vessel affected the organoleptic quality assessment of light beer with an essence content below 13%. This quality was assessed at a significantly lower level when the beer was served in a tulipglass compared to the other two vessels.

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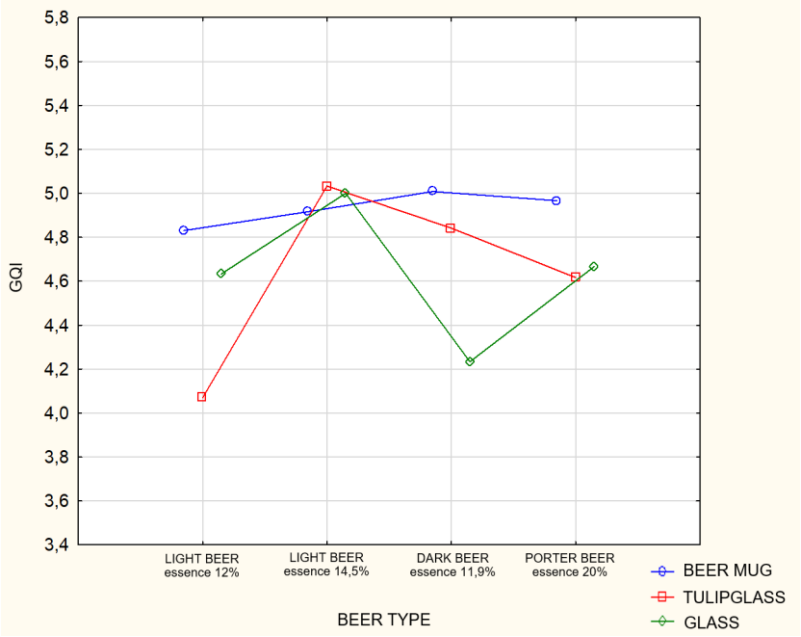


Figure 1. Organoleptic quality level of individual beer types assessed in different vessels

The research results indicate the existence of statistically significant differences in the assessment of the organoleptic characteristics of different beers served in different glasses (Table 6).

Table 6. Organoleptic characteristics of different types of beer depending on the type of vessel (The symbol * indicates significant differences in the level of the feature depending on the type of vessel)

	light beer with essence content 12%	light beer with essence content 14%	dark beer with essence content 11,9%	porter beer with essence content 20%
	p value			
Odour	0,379	0,511	0,333	0,804
Taste	0,015*	0,431	0,245	0,176
Palatability	0,014*	0,623	0,269	0,133
CO_2 saturation	0,042*	0,930	0,116	0,400
Bitterness	0,023*	0,556	0,174	0,499

Significant differences in taste, palatability, saturation and bitterness depending on the type of vessel were noted for light beer with an essence content 12%.

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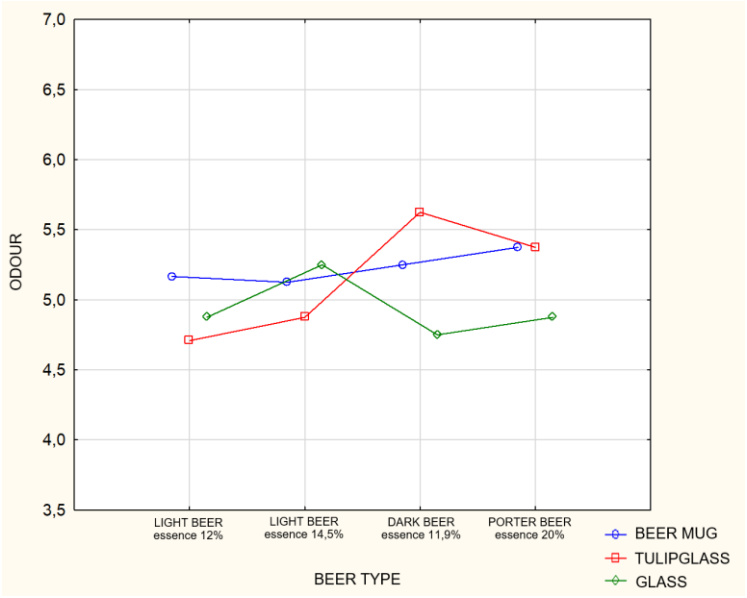


Figure 2. Odour of different types of beer evaluated in different vessels
Source: own study

At a significance level of 0.05, it can be concluded that the type of container had no effect on the odour assessment results for all beer varieties (Figure 2).

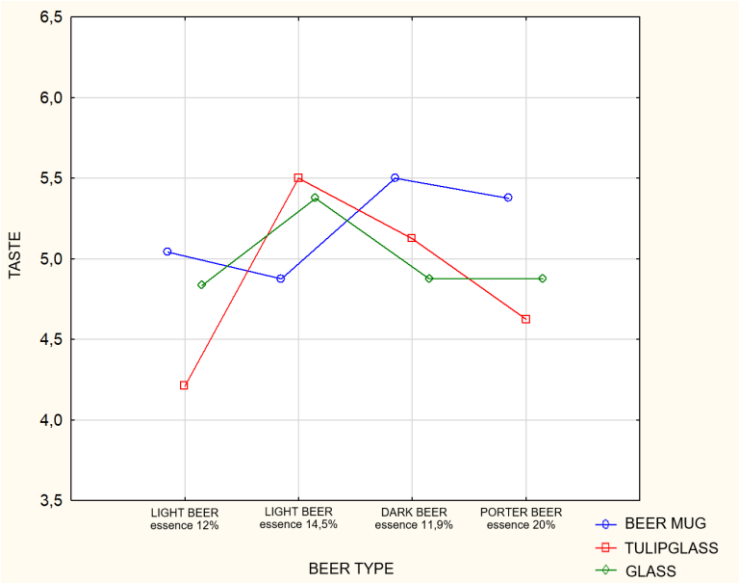


Figure 3. Taste of different types of beer evaluated in different vessels
Source: own study

The taste of a light beer with an essence content 12% served in a tulip glass was assessed at a lower level than beer served in the other two types of vessels (Figure 3). Differences are noted in the case of porter beer (average scores for samples in a glass are higher by about 0.8 points than the average scores for samples in a tulipglass), but these differences are not statistically significant.

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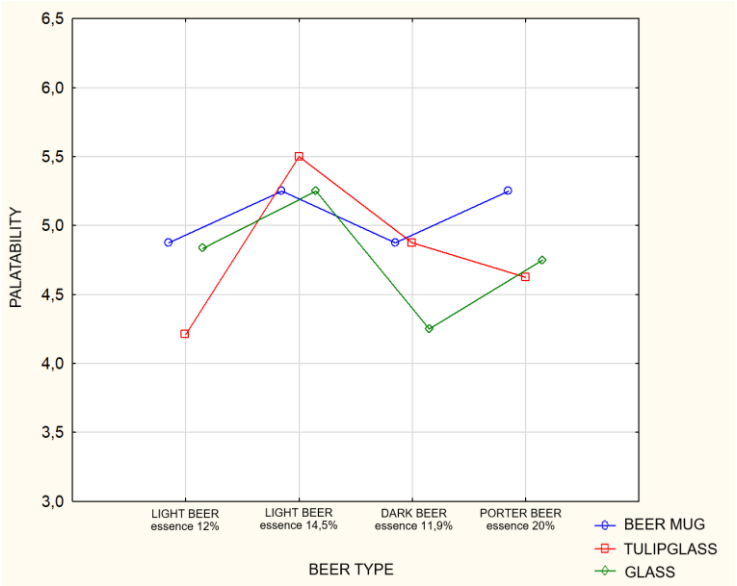


Figure 4. Palatability of different types of beer evaluated in different vessels
Source: own study

In the case of light beer with an essence content 12% the palatability of this beer served in a tulip glass was assessed at a lower level than the palatability of the same beer served in a glass or in a beer mug (Figure 4). Differences are noted in the case of the palatability scores for the other beer varieties. There are some differences in the case of porter (the average scores for the samples in a mug are higher by approximately 0.7 points than the average scores for the other samples), but these differences are not statistically significant.

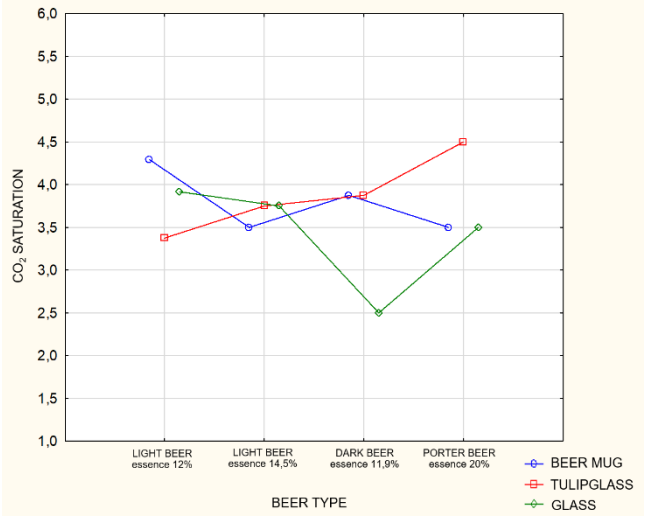


Figure 5. CO_2 saturation of different types of beer evaluated in different vessels
Source: own study

The saturation of a light beer with an essence content 12% served in a tulip glass was assessed at a lower level than beer served in a mug (Figure 5). The type of vessel did not affect the results of the assessment of the saturation of other types of beer. Differences are noted in the case of dark beer (average scores for samples in a glass are lower by about 1.5 points than the average scores for samples in a mug and a tulipglass), but these differences are not statistically significant.

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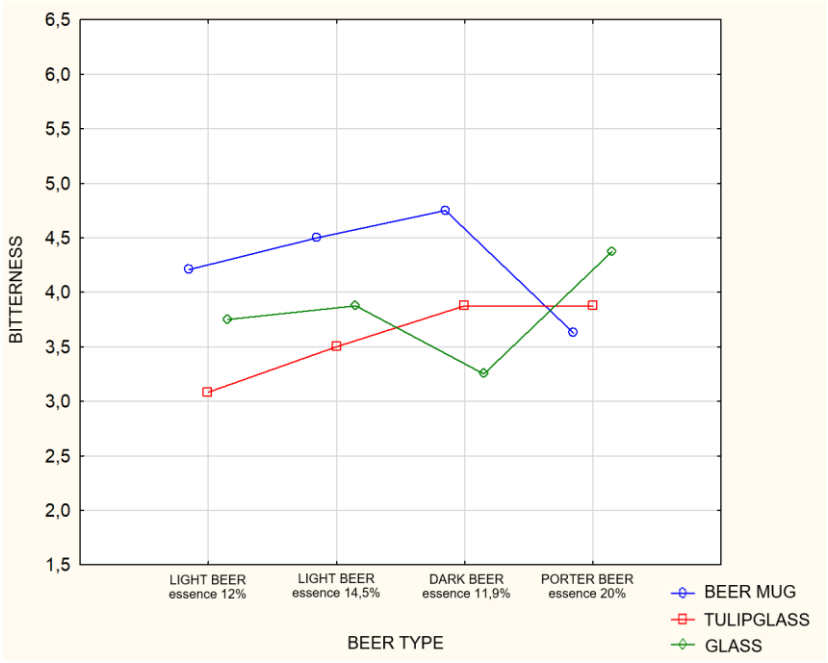


Figure 6. Bitterness of different types of beer evaluated in different vessels (mean values)
Source: own study

The bitterness of a light beer with an essence content 12% in a tulip glass was assessed at a lower level than beer served in a mug (Figure 6). Differences are noted in the case of dark beer (average scores for samples in a glass are lower by about 1.5 points than the average scores for samples in a mug and a tulipglass), but these differences are not statistically significant.

4. Discussion and conclusions

The conducted research expands the current knowledge on the influence of the shape of the vessel on the experience of drinking beer. When people are aware of the shape properties of the glass that they are drinking from (which is normally the case), then serving beer and wine in curved glasses brings out the fruitiness in the drink (Cliff, 2001) (Mirabito et al., 2017) (Ribeiro et al., 2021). In such cases, it is natural to consider the shape features of the glassware as affecting physicochemical properties of the volatiles in headspace over the glass. But it would seem more likely that it is the psychologically determined correspondence between taste and shape, especially given research showing that simply varying outer texture of drinking vessel can also bias taste ratings (Spence, 2023).

The choice of the drinkware could deeply affect consumer perception during beverage consumption. Several studies investigating drinking experiences have focused on how the presentation of a beverage in a particular type of container influences its perceived quality and appropriateness. Research in this area has consistently demonstrated that participants tend to evaluate beverages more positively when they are served in vessels that are regarded as suitable or “appropriate” for that specific drink (Spence & Doorn, 2017). This suggests that the physical context of consumption — particularly the choice of glassware — can significantly shape sensory expectations and subjective experience.

The idea of what constitutes an appropriate container, however, is not universal. It is often derived from previous personal experiences, social norms, and cultural conventions that associate certain beverages with specific forms of glassware. Over time, these learned associations establish a kind of perceptual template that informs consumers’ expectations about how particular drinks should be served. For instance, the shape and style of a wine glass, beer mug, or cocktail glass carry symbolic meanings that guide perceptions of quality, taste, and even authenticity. Consequently, some glass types have come to be perceived as inherently better suited for certain beverages than others (Casales-Garcia et al., 2023).

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Taking into account the above studies, certain conclusions can be drawn regarding the research we conducted. Light beer with an essence content of less than 12% served in a tulip glass has been assessed worse in every single tested trait. Odour, taste, saturation, palatability, bitterness and general quality index (GQI) have been perceived worst when the beer was served in tulip glass. It seems that tulip glass is particularly unsuitable for this type of beer.

The experimental results showed how the characteristics of a glass could affect beverage bouquet and flavour, and suggest that their rational optimization, based on experimental data, could enhance the consumer enjoyment of it.

This study leads to similar conclusions to those drawn by (Ribeiro et al., 2021) that the shape of the glass can influence consumer expectations regarding different beers. This conclusion leads to some practical applications namely that most expected combination of beer and glasses could be used by bar or pub owners to deliver a better experience to their consumers. Additionally, these findings can also lead to new market strategies by defining a specific combination of beverage and glass shape that the consumers expect to see. Designersneed to manage to comprehend and translate users' requirements into corresponding functionality and pleasing aesthetics (Li et al., 2024).

Another practical application of this study emerges. It has been suggested that effective interventions for changing routine or habitual behaviours should acknowledge the important role of automatic, non-conscious processes in shaping these behaviours. (Langfield et al., 2022) These two practical applications can be contradictory. The brewing industry, retailers, and restaurant owners are more interested in increasing alcohol consumption. Institutions such as the National Center for Addiction Prevention are working to reduce alcohol consumption. Knowledge about drinking behaviour would help to form any regulation-based policies, especially given that these policies are likely to be resisted by producers and retailers of the drinks targeted by the policy (Pomeranz & Brownell, 2014).

Last but not least practical application emerges from this study. In the contemporary context of sustainability, it is imperative to refrain from purchasing goods that do not fulfill an essential purpose. Consumers who possess an understanding of the relationship between the material properties of glass and the characteristics of beverages are better positioned to make deliberate and informed purchasing decisions. Accordingly, they should select glassware that optimally corresponds to the types of drinks they consume. From the producers' perspective, this awareness creates enhanced opportunities to design and supply products that align more precisely with consumer preferences and sustainability objectives. Nevertheless, this study has several limitations. The research focused primarily on how the shape of the glass influences the drinker's perception of beer with various essence content. However, only undecorated glassware was examined in this study. It would be worthwhile to assess how visual elements, such as decorative patterns or brand logos, might alter the drinker's perception. With the help of the insights gained, products can be better matched to customers' preferences. As a result, customers' needs are addressed early in the product design process, the likelihood of complaints is reduced. These observations highlight the potential for further research on the interaction between various beer types and glass designs, opening new avenues for understanding user experience.

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RECOGNISING EMPLOYEES' COMPETENCES THROUGH VERIFIABLE MICRO-CREDENTIALS: ALIGNING HIGHER EDUCATION AND EMPLOYERS' NEEDS IN THE DIGITAL ERA*

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Abstract. Labour markets in the digital and Industry 5.0 era increasingly expect timely and trustworthy evidence of what employees can actually do, not only which formal qualifications they hold. However, employers often face information asymmetries: CVs and traditional diplomas provide limited insight into specific competences, especially when they are developed through short courses and non-formal learning. This paper examines how verifiable micro-credentials and digital badges can reduce these asymmetries by making learning outcomes, assessment and evidence transparent and machine-readable for employers. Based on a narrative, concept-centred review of 30 peer-reviewed articles (2016–2025), the study develops a three-layer model (pedagogical–assessment, technological–verification, recognition–policy) and a minimum interoperability profile for micro-credentials. The model links competence needs signalled by employers to learning outcomes, assessment tasks and authentic artefacts that can be recognised both in formal higher education and in flexible, work-based and non-formal settings. The paper outlines practical decision rules and an implementation roadmap for higher education institutions to issue verifiable micro-credentials that are readable and useful for employers. The contribution is an actionable framework that supports skills-based recruitment, internal mobility and upskilling strategies while keeping the recognition of employees' competences at the centre.

Keywords: verifiable micro-credentials; digital badges; employee competences; skills recognition; labour market signalling; employers' needs; Industry 5.0; higher education.

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JEL Classifications: M53, M54, O31

Additional disciplines: educology; information and communication

1. Introduction

Digitalisation, automation and the green transition are changing how companies and entrepreneurs create value, organise work and compete in markets. Under the Industry 5.0 and Society 5.0 paradigms, technology is increasingly expected to support human-centred, sustainable development, not only productivity gains (Hossain & Purdy, 2024; Atay et al., 2025). Production and service systems become more data-intensive and integrated along digital value chains (Voulgaridis et al., 2022; Chuma & Ngoepe, 2025). For employers this means a growing dependence on employees who combine specialised technical competences with transversal skills such

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as problem solving, collaboration and continuous learning. Evidence from Industry 5.0 initiatives and regional upskilling programmes shows that large segments of the workforce must be reskilled or upskilled in short, targeted learning cycles closely linked to the workplace (Doyle-Kent & Shanahan, 2022; Doyle-Kent et al., 2022; Pinto et al., 2024). The ability to identify, verify and deploy suitable competences has therefore become a strategic condition for innovation, entrepreneurship and sustainable business development.

Labour markets, however, still rely mainly on traditional credentials and self-reported CVs as signals of capability. Cross-country studies indicate that when the level and field of education are aligned with occupational structures, workers enjoy higher earnings and lower unemployment risk; when alignment is weak, both individuals and firms bear the cost of mismatch (Vogtenhuber, 2018; DiPrete & Chae, 2023). Conventional degrees describe programmes in broad terms and provide limited insight into what an employee can actually do in specific digital or green transition tasks. This information gap is even more pronounced for competences gained through short courses, employer-led training, non-formal programmes and informal workplace learning. For entrepreneurs and managers seeking to build agile teams, it is difficult to judge the level, scope and reliability of such learning, even when it is crucial for new business models in areas such as smart manufacturing, circular economy or data-driven services.

In response, higher education institutions (HEIs), training providers and companies are experimenting with more flexible, modular forms of learning. Short, demand-driven technical programmes and micro-courses are used to tailor skills to sectoral needs and to support lifelong learning in applied fields (Mena-Guacas et al., 2023; Pinto et al., 2024). Micro-credentials and digital badges package these learning experiences into focused units that can stand alone or be stacked into larger qualifications. The literature highlights that such micro-credentials can make learning more responsive to employer demand, support career transitions and widen access to upskilling opportunities beyond full-degree pathways (Shanahan & Organ, 2022; Yılık, 2025). Sector-specific examples show how micro-credentials are co-designed with industry to support life-long learning for urban energy transitions and renewable energy ecosystems (De Rosa et al., 2024) or to personalise professional learning pathways (Vordenberg et al., 2024; Fan et al., 2024).

At the same time, the rapid expansion of micro-credential initiatives raises governance and recognition issues. HEIs emphasise robust pedagogy, clear learning outcomes and authentic assessment (Shanahan & Organ, 2022; Catenazzi et al., 2025), while employers need simple, comparable and trustworthy signals that can be integrated into recruitment, internal mobility and competence management processes. Without common principles for describing and verifying micro-credentials, there is a risk of fragmentation: many small certificates that are difficult for employers to interpret and therefore have limited business value. Existing research on digital badges and holistic competencies shows that, in practice, evidence of specific competency achievement is often embedded in final degrees and remains invisible, and that systems for documenting and reporting such competencies are fragmented and not well aligned with labour-market needs (Chan & Chen, 2022). This underlines the importance of moving from generic claims about “skills” to verifiable, portable and employer-readable competences. Technological developments offer tools to address these problems but also introduce new layers of complexity. Open digital badges based on recognised data models allow structured information about learning outcomes, assessment and evidence to be attached to a visual credential (Catenazzi et al., 2025). Emerging wallet-based and blockchain-enabled solutions promise tamper-evident, privacy-aware and portable credentials that employees can share directly with employers across organisational and national boundaries (Alsobhi et al., 2023; El Koshiry et al., 2023; Gottlieb et al., 2024). New digital “wallets” allow employees to share secure, hard-to-fake credentials with employers with a single click, regardless of which institution issued them. Interoperability frameworks and reference models stress the need for aligned semantics and verification processes if credentials are to move reliably between HEI systems, learner wallets and employer platforms (Chukowry et al., 2021; Perisic et al., 2023). Yet much of this work approaches credentials primarily from a technological or educational perspective and pays less attention to how micro-credentials function as labour-market signals and management tools inside firms.

The specific problem addressed in this paper is how to verify obtained competences of employees in a way that meets employers’ needs in the digital era, while remaining feasible for HEIs and compatible with European transparency instruments. The article considers competences acquired in formal degree programmes together

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with those developed in non-formal and informal learning, treating them as parts of a single portfolio that must be visible and trustworthy for employers. It asks three questions: (1) what requirements do employers and entrepreneurial firms have for the way competences are described and verified in digital credentials; (2) how can HEIs design micro-credentials and digital badges so that these requirements are met across formal, non-formal and work-based learning; and (3) what minimum data and governance rules are needed for a verifiable micro-credential profile that is both technically interoperable and economically meaningful for companies.

This article is unique in two respects. First, building on the call for systematic documentation and recognition of competencies in higher education (Chan & Chen, 2022; Catenazzi et al., 2025), it explicitly reframes micro-credentials as a strategic instrument for entrepreneurship, human-capital management and sustainable business development, rather than as a purely educational innovation. It integrates insights from Industry 5.0 skills demand, competence mismatch research and digital credential technologies to propose a three-layer model (pedagogical–assessment, technological–verification, recognition–policy) that is oriented to employer decision-making. Second, it translates this model into a practical, stepwise profile for verifiable micro-credentials that can be read by employers, aggregated at company level and used to support skills-based recruitment, internal mobility and continuous upskilling strategies aligned with green and digital transitions (Shanahan & Organ, 2022; Alsobhi et al., 2023; De Rosa et al., 2024; Atay et al., 2025). In doing so, the paper positions micro-credentials at the interface between education and business, contributing to the economics, management and entrepreneurship focus of the journal.

2. Concepts and theoretical foundations

2.1. Definitions

Micro-credential. A micro-credential is a record of focused learning achievement, awarded by a trusted provider after assessment against defined standards; it has standalone value and can contribute to larger qualifications, with description elements that include learning outcomes, assessment type, quality assurance, and—where possible—ECTS and EQF level (Zain, 2023; Catenazzi et al., 2025).

Open badge (digital badge). An open badge is a digital credential consisting of a visual image and embedded metadata—such as issuer, description, criteria, evidence, recipient, validity and revocation—that is human-readable, machine-verifiable, cryptographically signed, and tamper-evident under the 1EdTech Open Badges specification (Catenazzi et al., 2025).

Stacking. Stacking refers to combining several short learning experiences or badges so they either remain standalone or accrue into a larger micro-credential or qualification pathway (Shanahan et al., 2022; Zain, 2023).

Portfolio and wallet. A learner portfolio is an e-portfolio that aggregates study documents and evidence of learning for sharing in academic processes (Gottlieb et al., 2024). A credential wallet is a learner-controlled application that stores and manages issued credentials—often alongside institutional wallets for issuers—supporting collection, presentation, and verification across contexts (Gottlieb et al., 2024).

Interoperability. Interoperability is the capacity of credentials to be issued, read, and verified across platforms through common data models and formats such as 1EdTech Open Badges, the W3C Verifiable Credentials (VC) data model, and the European Learning Model (ELM), enabling portability and machine processing (Catenazzi et al., 2025).

Verification models. In issuer-hosted verification, systems like Blockcerts publish an issuer profile and public key used to validate signatures and revocation status of a credential stored on or referenced by a public ledger (Gottlieb et al., 2024). In decentralised verification, learners present W3C VCs linked to Decentralised Identifiers (DIDs), reducing reliance on centralized authorities and enabling privacy-preserving proofs within trust frameworks (El Koshiry et al., 2023; Gottlieb et al., 2024).

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Scope note. These definitions are aligned with the article's focus on a narrative, concept-centred review of micro-credentials, digital badges, and verifiable credentials in higher education and VET, ensuring consistent terminology across the manuscript (Shanahan et al., 2022; Catenazzi et al., 2025).

2.2. Ecosystem: learner–higher education institution–employer

Learner. Learners seek clear, portable, and recognised evidence of competence; they value transparency, ownership, and the ability to aggregate and present evidence through an e-portfolio or credential wallet across platforms (Perisic et al., 2023; Catenazzi et al., 2025).

Higher education institution (HEI). HEIs design learning that is outcomes-based, use authentic assessment, ensure quality assurance, and issue verifiable badges aligned with qualification levels and credit systems (De Rosa et al., 2024; Catenazzi et al., 2025).

Employer. Employers signal in-demand competences and expect intelligible artefacts (e.g., code, prototypes, reports) and verifiable badges; coordinated interaction among the three actors narrows the study–work gap (Shanahan & Organ, 2022; De Rosa et al., 2024).

Interaction logic. The ecosystem operates as a coherent chain: labour-market signals → formulation of learning outcomes → authentic assessment → portfolio evidence → badge with metadata → verification → recognition. In practice, outcome-aligned, team-based and experiential tasks generate employer-readable artefacts that can be referenced in badge metadata and presented from a learner portfolio/wallet (Shanahan & Organ, 2022; Perisic et al., 2023; Catenazzi et al., 2025).

Industry 5.0 anchoring. Human-centricity, sustainability, and resilience imply "visible" evidence that is machine-readable and verifiable. Aligning learning outcomes and assessment criteria with evidence URLs produces tamper-evident artefacts that employers can automatically read and check, setting up Section 4.1 where employer needs are mapped to the minimum metadata profile and interoperability requirements (Chukowry, 2021; El Koshiry, 2023; Catenazzi, 2025).

2.3. Standards and recognition

Metadata and traceability. Badge metadata must encode, at minimum, the learning outcomes (LO)→assessment→evidence chain plus credit and level, so that credentials align with qualification systems and credit practice (e.g., ECTS, EQF) and remain machine-readable across platforms (Catenazzi, 2025).

Quality assurance. Combine internal (programme) and external (institutional/partner) QA: publish transparent assessment criteria, an evidence typology, and validation procedures to enable cross-institution comparability of badges (Shanahan & Organ, 2022; De Rosa, 2024). As for implications, adopting nationwide and regional frameworks, using digital stacking tools, and operating on decentralized blockchain-like verification technologies to realize the recognition and quality assurance of micro-credentials would best serve the interests of the micro-credential stakeholders, including higher education itself as a scientific and institutional actor (Yılık, 2025).

Interoperability guidelines. Follow open, **heterogeneous** interoperability principles so that data structures, semantics, and flows between the LMS, e-portfolio, and wallet remain compatible, verifiable, and portable (Perisic, 2023). Use **Open Badges 3.0** with mappings to **W3C Verifiable Credentials (VC)** and the **European**

Learning Model (ELM, Europass) supports automated reading and verification.

Governance and risk. Select verification mechanisms based on scale, privacy and durability: issuer-hosted (digital signature/public key and revocation checks) for institutional contexts; decentralised registration (e.g., blockchain) where cross-institution recognition, tamper-evidence and long-term availability are required (El Koshiry, 2023; Gottlieb, 2024). Define roles, keys, revocation, and audit trails up front.

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Stacking and institutional recognition. From an employer's perspective, the information on credit volume (ECTS) and qualification level (EQF) in each badge works like a "scale" and "difficulty label" for the competence signal. When several badges share compatible levels and credits, higher education institutions can group them into larger micro-credentials or even components of degree programmes. For companies, this stacking reduces micro-fragmentation: HR specialists can interpret a bundle of badges as a coherent block of study rather than a set of isolated short courses. Machine-readable metadata, based on Open Badges, W3C Verifiable Credentials and the European Learning Model, make it possible to check automatically who issued the badge, at what level and on what kind of evidence. This lowers the cost and risk of relying on micro-credentials in recruitment and internal promotion decisions.

Data protection and lifecycle. Apply data minimisation and lifecycle controls, especially when evidence includes assessment artefacts; expose links (evidence URLs) while keeping personal data and sensitive files under appropriate access policies.

Bridge to Sections 4.3 and 6. Section 4.3 details the minimum field set, and Section 6 translates these standards into HEI implementation steps.
The standards-to-recognition pathway connects assessment and learning objectives to transferable, verifiable credentials, as illustrated in Figure 1.

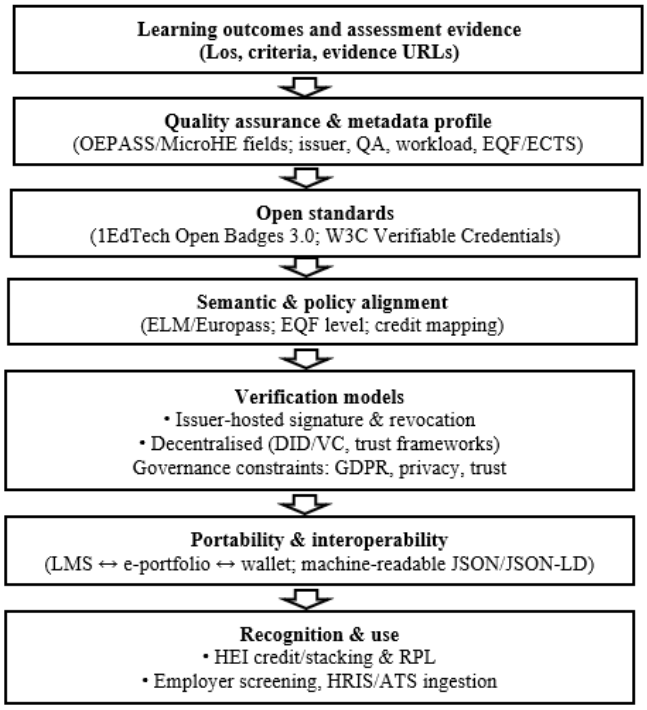


Figure 1. Standards-to-recognition stack for micro-credentials
(Open Badges 3.0 ↔ W3C Verifiable Credentials, aligned with ELM/EQF)

3. Methodology

3.1. Review type

A narrative, concept-centred review was conducted, focusing on the micro-credential ecosystem and its interlinked components: the LO→assessment→evidence chain, open digital badges, interoperability, verification models, quality/recognition, and pedagogy in short courses. The synthesis integrates conceptual and technical strands to build an institutional model for higher education, using a deductive–inductive coding approach described in Sections 3.6–3.7.

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3.2. Search strategy and data sources

Evidence base. The review draws exclusively on a pre-specified corpus of 30 peer-reviewed articles selected for this study, predominantly hosted on ScienceDirect/Elsevier and spanning 2016–2025. No additional records were sought beyond this set.

Scope and language. English-language journal articles (research and review).

Screening within the set. Items were screened for relevance to at least one of the target concepts: *micro-credential / microcredential; open badge / digital badge; interoperability / W3C Verifiable Credentials; portfolio / wallet; verification / blockchain; ECTS / EQF; Industry 4.0 / 5.0*. All 30 met inclusion aims for the concept-centred synthesis; therefore, counts of excluded items and PRISMA flow were not applicable to this pre-specified corpus.

Data handling. A standard extraction form captured bibliographic details, context/type, key definitions, ecosystem roles, LO→assessment→evidence elements, badge metadata, interoperability aspects (LMS–e-portfolio–wallet flows and semantics), verification type (issuer-hosted / decentralised) and conditions, quality/recognition, and pedagogy. Extraction and coding procedures are detailed in Sections 3.5–3.7, with audit-trail materials noted in Section 3.8.

3.3. Inclusion and exclusion criteria

Inclusion

- **Topical relevance:** direct coverage of at least one target concept: micro-credentials / digital (open) badges; LO→assessment→evidence chain; interoperability (Open Badges 3.0, W3C Verifiable Credentials, ELM/Europass); verification (issuer-hosted vs decentralised, blockchain); quality/recognition (ECTS, EQF); pedagogy in short courses.
- **Publication type and quality:** peer-reviewed journal articles (research or reviews) with accessible full-text PDF.
- **Context:** higher education and/or VET; employer-recognition or labour-market alignment considered a plus.
- **Language and period:** English; 2016–2025**.**
- **Fit to synthesis:** provides conceptual, methodological, or technical material usable for the narrative, concept-centred integration.

Exclusion

- Out of scope (e.g., digital badges with no assessment/evidence linkage; blockchain papers without education/credentialing focus).
- Non-peer-reviewed items (editorials, opinion pieces, short notes) or inaccessible full text.
- Duplicates or near-duplicates.
- Languages other than English; contexts limited to K-12 without transferability to HE/VET.

Application to the corpus. The criteria were applied to the pre-specified set of 30 peer-reviewed PDFs selected for this study; all 30 met inclusion aims for the concept-centred synthesis. No additional records were sought beyond this set; consequently, PRISMA flow counts are not applicable to this design. Screening and eligibility checks used the extraction form in Section 3.5 and coding categories in Section 3.6 to ensure consistency with the study's objectives.

3.4. Screening flow

This review used a pre-specified corpus of 30 peer-reviewed articles. A simple screening flow was applied within this set: (i) title/abstract relevance to at least one target concept; (ii) full-text confirmation of alignment to the LO→assessment→evidence chain, interoperability/verification, or quality/recognition; (iii) inclusion for concept-centred synthesis. No PRISMA counts are reported because no additional records were sought beyond the pre-specified corpus.

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3.5. Data extraction

A standardized extraction form was used for each source to capture:

- bibliographic details and study context/type;
- key definitions;
- ecosystem roles;
- LO→assessment→evidence elements;
- badge metadata (e.g., LO_ID, learningOutcomes, assessmentCriteriaURL, evidenceURL, creditECTS, levelEQF, issuer, issueDate/validThrough, badgeClass/assertion, signature/publicKey, verification);
- interoperability aspects (LMS–e-portfolio–wallet flows and semantics);
- verification type (issuer-hosted / decentralised) and conditions;
- quality/recognition (QA, transparency, benchmarking);
- pedagogy (principles for short courses).

Extraction fields are aligned with the minimal interoperability profile specified in Section 4.3 to ensure machine-readable traceability from learning outcomes to recognition and consistent, cross-institution comparability.

3.6. Coding scheme

A deductive–inductive coding approach was applied. An initial codebook was seeded from the conceptual domains of the review and iteratively refined during pilot coding to ensure alignment with the extraction fields in Section 3.5 and the results structure in Sections 4.1–4.7. Unit of analysis: statement or subsection fragment. Multiple coding was allowed where passages spanned several domains; disagreements were addressed through iterative re-review and consensus, with codebook updates recorded in the audit trail (see Section 3.8).

Codebook categories (a–g):

a) Ecosystem (learner–HEI–employer interactions and labour-market signals);
b) LO–assessment–evidence chain (intended/achieved LOs, authentic assessment, portfolio artefacts);
c) Badge metadata (minimum profile fields and traceability requirements);
d) Interoperability (LMS–e-portfolio–wallet flows; semantic/data-model alignment);
e) Verification (issuer-hosted vs decentralis(e)d; keys, signatures, revocation, trust frameworks);
f) Quality / recognition (QA, transparency, ECTS/EQF mapping, stackability, inter-institution recognition);
g) Pedagogy (short courses) (experiential/team-based tasks that generate employer-readable artefacts).

Traceability and outputs. Codes were mapped to the extraction fields (Section 3.5) to maintain machine-readable traceability from learning outcomes to recognition and to the results subsections (4.1–4.7) for thematic synthesis. The coding matrix (categories × sources) is provided in Table 1 as documentation of coverage and triangulation.

Table 1. Coding matrix (categories × sources)

	a) Ecosystem (learner–HEI–employer)	b) LO–assessment–evidence chain	c) Badge metadata (minimum profile)	d) Interoperability (LMS–e-portfolio–wallet; semantics)	e) Verification (issuer-hosted vs decentralised)	f) Quality / recognition (ECTS/EQF; stackability)	g) Pedagogy (short courses; authentic tasks)
S01 Catenazzi (2025)			✓	✓		✓	
S02 Gottlieb et al. (2024)	✓			✓	✓		
S03 Shanahan & Organ (2022)	✓					✓	✓
S04 El Koshiry et al. (2023)					✓	✓	
and others		✓					

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3.7. Analysis procedure

A staged procedure was applied within the pre-specified 30-article corpus:

1. **Pilot coding (n=3):** the initial codebook was checked against sample sources to refine code definitions and examples, ensuring alignment with Section 3.5 fields and the planned results structure (Sections 4.1–4.7).
2. **Full-corpus coding (n=30):** statements and subsection fragments were coded deductively–inductively across seven domains (ecosystem; LO–assessment–evidence; badge metadata; interoperability; verification; quality/recognition; pedagogy). Multiple coding was allowed where passages spanned several domains.
3. **Thematic synthesis:** codes were grouped into themes and subthemes and cross-walked to the LO→assessment→evidence→badge chain and to interoperability/verification requirements.
4. **Model consolidation:** themes were integrated into a three-layer model (pedagogical–assessment; technological–verification; recognition–policy) and into the minimum interoperability profile used in Section 4.3.
5. **Quality checks:** an audit-style review verified that each substantive claim was supported by multiple sources and that codebook updates were recorded and traceable (see Section 3.8).

3.8. Reliability and transparency

Audit trail. The audit trail comprises the coding matrix (categories × sources), the codebook with versioned updates, and a decision log documenting notable coding changes; materials are available on request to support verification of the analytic path.

Reproducibility. Study parameters (keywords, database, time window, inclusion criteria) are specified in Sections 3.2–3.3 to enable replication using the same pre-specified corpus design.

Bias mitigation. Multiple coding was permitted; potential disagreements were resolved by iterative re-review and consensus. Agreement thresholds of ≥85% overlap or Cohen's $\kappa \geq 0.70$ were treated as acceptable for risk-prone passages.

3.9. Ethics and limitations

Ethics. The review analysed published, peer-reviewed documents only; no human participants or personal data were involved. Sources consisted of publicly available PDFs selected a priori, and analysis focused on conceptual and technical content relevant to micro-credentials, badges, interoperability, and verification. Institutional ethics approval was not required for this document-based synthesis.

Limitations.

This review synthesises a pre-specified corpus of 30 peer-reviewed journal articles drawn from defined databases and a 2016–2025 window; grey literature and non-English studies may therefore be under-represented. The analysis is concept- and method-oriented and does not prescribe or empirically trial specific IT stacks or API-level implementations, and no meta-analytic effect sizes are estimated. Generalisation beyond higher education and VET contexts should be made cautiously, as long-term economic outcomes (e.g., ROI, employment effects) were not quantitatively evaluated. Finally, results are bounded by rapidly evolving credential standards (Open Badges 3.0 / W3C VC / ELM/EQF), which may necessitate periodic updates as ecosystems mature.

4. Results: thematic synthesis

4.1. Ecosystem interaction and employer signals

Labour-market signals (e.g., job postings, employer surveys) inform the formulation of learning outcomes and the design of authentic, team-based tasks that generate employer-readable portfolio artefacts (code, prototypes, reports). These signals translate into requirements for portable, machine-readable and verifiable credentials so that evidence can be inspected beyond the issuing HEI (Shanahan & Organ, 2022). To support cross-institution recognition, the resulting badges expose a minimal metadata set (e.g., evidenceURL, issuer, creditECTS, levelEQF) aligned with open standards and European models, ensuring semantic portability across LMS, e-portfolio and wallet contexts (Catenazzi et al., 2025; Perisic et al., 2023).

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4.2. The LO → assessment → evidence → badge chain

Learning outcomes are operationalised through authentic assessment; the resulting artefacts are referenced in the badge metadata to make the LO→assessment→evidence link explicit and machine-verifiable. Issuance follows Open Badges 3.0 with mappings to W3C Verifiable Credentials and ELM/EQF, enabling automated checks of issuer, level and credit and supporting stackability into modules or programme components (Catenazzi et al., 2025; De Rosa et al., 2024). Verification proceeds via issuer-hosted signature/revocation for institutional contexts or decentralised DID/VC models where cross-institution trust, tamper-evidence and long-term availability are required (Chukowry et al., 2021; El Koshiry et al., 2023; Gottlieb et al., 2024). This chain ensures end-to-end traceability from intended outcomes to recognised, employer-relevant credentials across systems.

4.3. Minimal badge profile (Open Badges 3.0 ↔ W3C VC ↔ ELM/EQF)

This subsection specifies the minimum machine-readable metadata required to ensure portability and verification across LMS, e-portfolio, and wallet contexts. Fields map to 1EdTech Open Badges 3.0, align with W3C Verifiable Credentials, and indicate ELM/EQF semantics for recognition.

Table 2. Minimum badge profile (fields, purpose, example)

Name	Purpose	Example
LO_ID	links the badge to a specific learning outcome	LO-ENG6-001
learningOutcomes	machine-readable description of achieved outcomes	”Builds a working prototype…”
assessmentCriteriaURL	public rubric/criteria reference	https://example.org/...
evidenceURL	link(s) to portfolio artefacts	https://example.org/...
creditECTS	workload for stacking/recognition	3 ECTS
levelEQF	qualification level where applicable	EQF 6
issuer	institutional issuer identifier	KVK – Faculty of Technology
issueDate / validThrough	issuance and (if applicable) validity	2025-05-01 / –
badgeClass	badge class/type	BadgeClass: Prototype Builder
assertion	unique assertion identifier	urn:uuid:1f2e-…
signature / publicKey	cryptographic signature and key reference	JWS / did:key:z6Mkh…
verification	verification method	Issuer-hosted / decentralised registry.

Implementation notes.

- The profile **must be JSON/JSON-LD**, signed, and consistently validated (signature, public key, revocation/verification endpoint).
- Exposed fields enable **automated checks** (issuer, level, credit, evidence) and **stackability** into modules or programme components.
- Choice of **verification method** depends on scale, privacy, and durability requirements: issuer-hosted for institutional contexts; **decentralised** (e.g., DID/VC with registry) for cross-institution trust and tamper-evidence.

4.4. Interoperability across systems

Interoperability requires aligned data models, semantics, and verification endpoints so credentials move reliably across the LMS → e-portfolio → wallet continuum. In practice, badges are issued in Open Badges 3.0 (JSON-LD) with mappings to W3C Verifiable Credentials and semantic anchors to ELM/EQF; the minimal field set in Table 2 (e.g., *LO_ID, learningOutcomes, assessmentCriteriaURL, evidenceURL, creditECTS, levelEQF, issuer, signature/publicKey, verification*) enables machine-readable traceability. Operational requirements include: (i) stable identifiers for outcomes and assertions; (ii) signed payloads and revocation status; (iii) resolvable evidence links; and (iv) portability between institutional systems and learner-controlled wallets. These requirements correspond to the standards-to-recognition flow summarised in Figure 1.

4.5. Verification strategies

Verification selection follows a context-sensitive decision path:

- **Scale & audience.** Internal or limited partner use → issuer-hosted signature/revocation; broad, cross-institution audiences → decentralised registration (e.g., DID/VC with registry) for tamper-evidence and longevity.

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- **Durability.** Short retention → issuer-hosted; long-term availability → decentralised.
- **Privacy & regulation.** Restrictive policies (GDPR constraints on evidence) → minimise on-chain content; keep **evidence URLs** off-chain while registering verifiable assertions.
- **Cost & latency.** Low/medium → issuer-hosted is sufficient; higher resilience/trust needs → decentralised is justified.
- **Sensitivity of artefacts.** Public metadata only → issuer-hosted suffices; artefacts driving credential decisions → prefer decentralised proofs with selective disclosure.
  This logic maintains alignment with Table 2 and ensures that verification choices preserve portability and recognition requirements across institutions.

4.6. Pedagogical considerations for short courses

Authentic, team-based assignments should produce employer-readable artefacts (e.g., code, prototypes, reports) that are explicitly referenced in badge metadata via evidence URLs. Outcomes must be assessable with transparent rubrics (assessmentCriteriaURL) so the LO → assessment → evidence link is auditable. Short courses benefit from concise outcome statements, calibrated workload (ECTS), explicit EQF levels where applicable, and portfolio practices that foreground artefacts rather than only grades. This ensures that pedagogical design directly feeds the minimal badge profile and later verification/recognition steps. One of the main findings is that short-term courses are primarily designed for experiential learning, and memory-related activities commonly used in traditional training are not typically included in short-term courses (Mena-Guacas et al., 2023).

4.7. Quality assurance and recognition

Quality assurance combines internal (course/programme QA) and external (institution/partner) checks to support comparability. A concise QA checklist should confirm: (i) declared outcomes and public rubrics; (ii) evidence typology and links; (iii) conformance with Open Badges 3.0 / W3C VC; (iv) mapping to ELM/EQF and clear ECTS workload; (v) working verification (signature, key, revocation endpoint); and (vi) data protection controls over evidence. Recognition proceeds when machine-readable metadata allow automated checks of issuer, level, credit, and evidence, enabling stacking into modules/components and portability across institutions and employer systems. However, over 70% of the reviewed studies did not issue certificates or badges for participants (Wang & Hu, 2025).

5. Integrated model and decision rules

5.1. Consolidated model

The integrated model combines three interacting layers that link intended learning to verifiable recognition across systems:

- **Pedagogical–assessment layer.** Clearly formulated learning outcomes are operationalised through transparent rubrics and authentic tasks that generate employer-readable artefacts (e.g., code, prototypes, reports). These artefacts are referenced in badge metadata via evidence links, preserving auditable traceability from LO to assessment and evidence (see Sections 4.1–4.2).
- **Technological–verification layer.** Minimum machine-readable metadata are issued in Open Badges 3.0 (JSON-LD) with mappings to W3C Verifiable Credentials and semantic anchors to ELM/EQF. Verification follows either issuer-hosted signature/revocation **or** decentralised DID/VC models depending on scale, privacy and durability needs (Sections 4.3–4.5).
- **Recognition–policy layer.** When level **(**EQF**)** and workload **(**ECTS**)** are exposed in metadata and evidence is resolvable, credentials can be stacked into modules or programme components and recognised across institutions and employer systems (Sections 4.6–4.7).

Together, these layers implement an outcomes→assessment→evidence→badge→verification→recognition chain that remains portable and auditable across the LMS–e-portfolio–wallet continuum, aligning with Figure 1 and Table 2 earlier in the manuscript.

5.2. Minimum interoperability profile

This subsection summarises the minimum profile required for portability and verification; detailed field names and examples are provided in Table 2 (Section 4.3).

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Mappings and conformance.

- Encode badges as Open Badges 3.0 and map to W3C VC to enable cryptographic verification and selective disclosure where required.
- Expose ELM/EQF semantics (level, workload) to support stacking and cross-institution recognition.
- Keep artefacts referenced via evidence URLs; avoid embedding personal data in signed payloads.

Validation and governance.

- Enforce signature checks, public-key resolution and revocation status at verification time (issuer-hosted or decentralised).
- Apply data-minimisation and lifecycle controls (GDPR): publish rubrics and evidence links transparently while restricting access to sensitive artefacts.
- Choose issuer-hosted verification for institutional contexts; prefer decentralised (DID/VC with registry) when cross-institution trust, tamper-evidence and long-term availability are required.

This minimum profile operationalises the three-layer model in 5.1 and maintains end-to-end machine-readable traceability from learning outcomes to recognised credentials across systems.

5.3. Decision rules and implementation steps

This subsection summarises the decision logic for applying the integrated model.

Verification choice.

- Issuer-hosted signature/revocation is suitable for internal or limited-partner use, lower cost, and short-to-medium retention.
- Decentralised (DID/VC with registry) is preferred for cross-institution recognition, tamper-evidence, and long-term availability.

Data model alignment. Every credential must conform to Open Badges 3.0 (JSON-LD) with mappings to W3C VC and semantic anchors to ELM/EQF, exposing the minimum fields from Table 2 (e.g., LO_ID, learningOutcomes, assessmentCriteriaURL, evidenceURL, creditECTS, levelEQF, issuer, signature/publicKey, verification).

HEI implementation sequence (pointer). (1) align LOs and rubrics; (2) declare the minimum metadata; (3) enable signing and verification; (4) pilot on a short course; (5) formalise recognition with partners. See Section 6 for the institutional, 8–10-step plan.

5.4. Bridge to institutional guidelines

Data-flow view. The integrated model in Section 5.1 describes the horizontal flow from learning outcomes (LO) → assessment → evidence → badge → verification → recognition across LMS–e-portfolio–wallet contexts.

Why this matters for implementation. The flow clarifies which fields must be present in the badge payload **(**Table 2**),** where verification occurs **(**issuer-hosted **vs** decentralised**),** and how metadata enable stacking and cross-institution recognition. This bridge sets up Section 6 (Guidelines for HEI implementation)**,** where the model is operationalised through concrete steps, QA checks, and risk controls.

6. Guidelines for HEI implementation

This section translates the outcomes→assessment→evidence→badge→verification→recognition chain into an institutional plan, aligned with Figure 1 (standards-to-recognition stack) and Table 2 (minimum badge profile).

6.1. Step-by-step implementation plan (10 steps)

1. Identify competence needs. Use labour-market analyses and employer input to prioritise domains and skills.
2. Formulate learning outcomes (LOs). Define assessable LOs and map each to EQF level and ECTS workload for recognition.
3. Set assessment criteria and evidence. Publish transparent rubrics; specify acceptable artefacts (e.g., code, prototypes, reports) to evidence LO attainment.

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4. Design the credential and minimum profile. Configure Open Badges 3.0 (JSON-LD) with the core fields in Table 2 (e.g., LO_ID, creditECTS, levelEQF, evidenceURL, issuer, signature/publicKey, verification) and mappings to W3C VC/anchors to ELM.
5. Enable issuer-hosted verification. Deploy signing and revocation checks to ensure immediate institutional verification and tamper-evidence.
6. Prepare decentralised registration. Integrate DID/VC-based options (registry or trusted third party) for cross-institution trust and long-term availability.
7. Integrate with LMS and e-portfolio/wallet. Automate issuance, viewing, and evidence linkage across LMS ↔ e-portfolio ↔ wallet.
8. Establish QA and stacking rules. Define internal QA, evidence typology, and how compatible micro-credentials stack into modules or programme components.
9. Set up inter-institution recognition. Align metadata with ELM/EQF and formalise recognition protocols with partners.
10. Monitor and evaluate. Track uptake, employer feedback, administrative cost, and outcomes (e.g., employability/ROI) to iterate the model.

6.2. Risks and mitigation

As summarised in Table 3, the key risks for HEI deployment—along with their potential impact and preventive/corrective measures—are aligned with the step-by-step plan in Section 6.1.

Table 3. Risks and mitigation

Risk / challenge	Potential impact	Preventive / corrective measures
System fragmentation across HEIs	Incompatible data formats; non-portable badges	Sectoral standardisation on Open Badges 3.**0** and ELM; shared profiles and validators
Unclear ROI / employer value	Slow adoption; weak recognition	Transparent rubrics; real evidence in portfolios; periodic impact reviews with employers
Privacy and data protection	Personal-data exposure	GDPR compliance; data minimisation; keep artefacts behind evidenceURL with access control
Limited technical capacity	Implementation errors; data loss	Staff training; shared guidelines; sandbox/testing environments and helpdesk
Divergent partner recognition	Uneven acceptance of credentials	Inter-institution agreements; ECTS/EQF mapping; automated validation tools
Low ecosystem trust	Slow rollout; stakeholder scepticism	Public verification endpoints; certified signatures; third-party attestations
Excessive data retention	Security risk; higher costs	Metadata lifecycle control; minimise payload content; clear revocation policies

These controls should be embedded in governance and QA (policies, procedures, and vendor SLAs) and monitored during pilots and rollout. Use Table 3 as a pre-flight checklist alongside the minimum badge profile in Table 2; unresolved high-impact items should block release until mitigated. Finally, the main challenges educators encountered were related to the platform, time, resources, awareness, and micro mindset (Fan et al., 2024). Practical recommendations include national digital standards, micro-credential training programmes and industry–government–academia partnerships. (Siriwardhana, Moehler, & Fang, 2025). Enterprise credential spear-phishing using look-alike domains can evade common email defenses, which motivates layered mitigations such as domain/IP whitelisting, DKIM/SPF checks, and domain-similarity detection (Al-Hamar et al., 2021). Blockchain technology provides a decentralized, distributed, and secure environment to ensure security and privacy preservation (Alsobhi et al., 2023). Short, online, self-paced courses ("micro-courses") are one approach to addressing these challenges (Clayback, LoCasale-Crouch, & Alamos, 2024). Continuing technical education and training is becoming a constant, while at the same time the demands on continuing education are changing towards flexible, demand-oriented and modularized learning settings (Poschauko, Kreuzer, Hirz, & Pacher, 2024). Findings show benefits (ergonomics, curriculum–industry alignment, green jobs) and risks (deskilling, inequality, rebound effects) (Chigbu & Makapela, 2025).

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6.3. Summary

HEI deployment should be phased: build internal QA and issuer-hosted verification first, then extend to decentralised registration and inter-institution recognition. Maintaining a tight link from LO and assessment to evidenceURL and the fields in Table 2 ensures machine-readable traceability and portability across systems and employer contexts.

7. Discussion

7.1. Positioning relative to prior work

The synthesis extends earlier treatments that either catalogued digital badges and European transparency instruments or focused narrowly on blockchain verification. Here, the pedagogical–assessment layer (LOs, authentic assessment, portfolio artefacts) is explicitly linked to technological verification and recognition-policy layers, closing the LO → assessment → evidence → badge → verification → recognition loop. By specifying a minimum interoperability profile and decision rules for issuer-hosted versus decentralised verification, the model moves beyond descriptive accounts toward an actionable, institution-ready pathway (Shanahan & Organ, 2022; Catenazzi et al., 2025; El Koshiry et al., 2023; Gottlieb et al., 2024). Evidence from comparative labour-market research shows that credentials continue to carry independent signalling power beyond measured skills; in coordinated market economies, the higher-education credential effect exceeds the standardised skill effect across countries (Vogtenhuber, 2018). This underlines the importance of making credential information as transparent and competence-based as possible. In a different context, Young's (2011) analysis of institutional separation and space in teacher education shows how programme design, organisational arrangements and physical settings shape which competences become visible and recognised. The model proposed in this article responds to these insights by using micro-credentials and portfolios to surface competences that might otherwise remain implicit and to encode them in forms that can be read by both higher education institutions and employers.

7.2. Practical implications for HEIs and employers

For HEIs, aligning outcomes, public rubrics and evidence URLs with Open Badges 3.0 (mapped to W3C VC and anchored to ELM/EQF) enables machine-readable traceability and stackability. Governance should require signing, key resolution and revocation checks; the choice between issuer-hosted and decentralised verification follows privacy, scale and durability needs. For employers, portable badges carrying verifiable links to artefacts (code, prototypes, reports) reduce screening uncertainty and support skills-based selection and progression. At the same time, empirical work on the returns to education shows that the premium for a college degree is accumulative, multidimensional and multigenerational, and should be considered at the household level (Alon & Mcdossi, 2025). This suggests that verifiable micro-credentials will complement rather than replace traditional degrees by adding transparent, competence-level information to an already powerful credential signal. To make this complementarity effective, educational institutions and organisations should offer flexible learning opportunities, such as online courses, micro-credentials and apprenticeships, to support professionals in acquiring new skills and staying relevant in the changing job market (Pinto et al., 2024).

7.3. Scope and limitations

Findings derive from a concept-centred synthesis of 30 peer-reviewed articles; no additional records were sought. The approach is conceptual–methodological rather than an IT blueprint, and it does not quantify economic effects (e.g., ROI) or long-term labour-market outcomes. Consequently, generalisation beyond HE/VET contexts should be cautious, and updates may be required as Open Badges/W3C VC/ELM evolve.

7.4. Directions for research and policy

Future work should test cross-institution recognition at scale (shared validators, DID/VC registries), measure outcomes for learners and employers, and refine selective-disclosure patterns for privacy-sensitive evidence. Policy efforts should standardise minimum profiles (fields, semantics, verification endpoints), embed QA and data-protection requirements, and support sector pilots that integrate LMS, e-portfolios and wallets under interoperable, verifiable credentials.

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Conclusions

This review synthesised recent work on micro-credentials to connect the LO → assessment → evidence → badge → verification → recognition chain into an actionable pathway for higher education and employers. The resulting three-layer model—pedagogical–assessment, technological–verification, and recognition–policy—keeps employer-readable artefacts at the centre while aligning credential data with Open Badges 3.0, mappings to W3C Verifiable Credentials, and ELM/EQF semantics (see Figure 1).

A minimum interoperability profile (see Table 2) specifies the core machine-readable fields—linking LOs, rubrics and evidence URLs to issuer identity, credit (ECTS), level (EQF), signature/public key, and verification method—so that credentials are portable across LMS, e-portfolios and wallets, and stackable into modules or programme components. This profile enables automated checks of issuer, level, credit and evidence, improving comparability and recognition across institutions.

Verification follows issuer-hosted signature/revocation for institutional contexts or decentralised DID/VC arrangements when cross-institution trust, tamper-evidence and long-term availability are required. The decision rules ensure privacy-aware, cost-appropriate and scalable assurance without embedding sensitive artefacts in signed payloads (evidence remains referenced via links).

For implementation, the ten-step plan in Section 6 operationalises governance, data modelling and systems integration, while Table 3 provides risk–mitigation controls to be embedded into QA and policy (e.g., standardisation on Open Badges 3.0/ELM, GDPR-aligned data minimisation, key management and revocation, inter-institution recognition protocols). Institutions can phase adoption: establish internal QA and issuer-hosted verification first, then extend to decentralised registration and partner recognition.

Overall, the model offers a coherent route from intended learning to verifiable, portable recognition—grounded in open standards and geared to Industry 5.0's human-centric skills agenda—thereby reducing ambiguity for HEIs and employers and providing a stable foundation for sector pilots and future evaluation.

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ARTIFICIAL INTELLIGENCE AND SUSTAINABLE ENTREPRENEURSHIP NEXUS: A REVIEW

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Abstract. This paper provides a bibliometric review of sustainable entrepreneurial intention in relation to artificial intelligence (AI). Based on a dataset of 1,855 peer-reviewed articles indexed in Scopus between 2015 and 2025, the paper makes use of co-citation analysis, keyword mapping, and trend evolution to analyse the evolution and frontiers of the field. There are four major themes: (1) AI-augmented entrepreneurial cognition, covering AI's relationship to ideation and innovation; (2) sustainability-driven motivation, focusing on environmental values and behavioural drivers influencing sustainable entrepreneurial intention; (3) entrepreneurship education; (4) ethical trust and legitimacy, addressing transparency and governance of AI applications. The results show that AI functions as a technological and cognitive facilitator, affecting the formation of entrepreneurial intentions and shaping pedagogical practices. This study not only contributes theoretically but also offers practical recommendations for educators, policymakers, and technology developers seeking to foster sustainable, ethical, and AI-based entrepreneurial ecosystems.

Keywords: Artificial Intelligence; Sustainable Entrepreneurship; Sustainable Entrepreneurial Intention; Bibliometric Review; Entrepreneurship Education; AI Ethics

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JEL Classifications: M53, M54, O31

1. Introduction

In the wake of accelerating ecological crises and technological disruption, the intersection of sustainable entrepreneurial intention (SEI) and artificial intelligence (AI) has emerged as a rapidly expanding research frontier (Appio et al., 2024). As entrepreneurs seek to reconcile economic ambition with environmental and social imperatives, AI is increasingly viewed not only as a technological enabler but also as a cognitive augmentation tool that transforms the entrepreneurial decision-making process (Bickley et al., 2025; Mohammed et al., 2025).

Recent scholarship underscores the dual role of AI in enhancing data-driven opportunity recognition and influencing entrepreneurial motivation through cognitive support systems (Giuggioli & Pellegrini, 2022). Studies highlight AI's contributions to sustainability-oriented business models, green innovation, and the evolution of entrepreneurial education (Ahmić & Šahović, 2025; Asad et al., 2025). However, despite a surge in research activity, the field remains conceptually fragmented and methodologically disjointed (Abushanab, 2024). Specifically, little is known about how AI reshapes the intentionality, value orientation, and trust dynamics underpinning SEI, particularly from a cross-disciplinary perspective (Gupta et al., 2023).

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Sustainable entrepreneurship (SE) involves business activities that create economic, environmental, and social value at the same time. Sustainable entrepreneurial intention (SEI) reflects an individual's motivation and willingness to take part in such activities in the future. SEI is often seen as a first step toward SE. In line with the Theory of Planned Behaviour, it represents the translation of sustainability-related values, social expectations, and perceived control into the decision to start or adapt a business toward sustainable goals. Studies show that values and future orientation influence SEI, which then leads to sustainable entrepreneurial actions (Thelken & de Jong, 2020). SEI has also been linked to attitudes and perceived behavioural control as strong predictors of action (Peng et al., 2021). In addition, evidence suggests that entrepreneurial intention can predict sustainable business behaviour, while risk perception plays a mediating role (Yang et al., 2022). Focusing on SEI helps explain how AI-supported tools may shape sustainability-oriented entrepreneurial thinking before real business action takes place.

While prior bibliometric studies have separately explored AI-driven entrepreneurship and sustainability-focused innovation, few have systematically mapped the knowledge structure, thematic evolution, and intellectual influence at the convergence of SEI and AI (Wadhwa & Bansal, 2024). The absence of integrative frameworks limits our understanding of how AI technologies affect the formation of sustainable entrepreneurial intentions across contexts. To address these gaps, the primary objectives of this study are: (1) To map the thematic evolution, co-citation structures, and keyword co-occurrence networks in the SEI and AI literature; (2) To identify key intellectual contributors, institutional collaborations, and publication trends; (3) To uncover emerging research hotspots and theoretical opportunities. Guided by these objectives, this study addresses the following research questions:

1. What are the prevailing research trends and thematic clusters at the intersection of SEI and AI?
2. Who are the most influential authors, institutions, and journals shaping this domain?
3. What research gaps and conceptual frontiers can be identified through bibliometric mapping?

By clarifying the intellectual architecture and developmental trajectory of SEI and AI research, this research provides a foundation for future interdisciplinary inquiry. The findings offer insights for scholars, educators, policymakers, and technologists aiming to foster responsible, AI-empowered, and sustainability-oriented entrepreneurial ecosystems.

The remainder of the article is structured as follows: Section 2 presents the theoretical background and critically analyses the background scholarship at the confluence of sustainable entrepreneurial intentions and artificial intelligence, with a view to highlighting still-existing conceptual or methodological deficiencies. Section 3 describes the research design, including the data-gathering strategy, bibliometric procedures, and analysis approaches used to identify the intellectual and thematic organisation of the field. Section 4 presents and analyses the empirical findings, including trend analyses, co-citation networks, and keyword co-occurrence patterns, to reveal prevailing and emerging research themes. Section 5 discusses the theoretical implications as well as practical implications for academia, policy, and technology development. Finally, Section 6 provides the conclusion, addresses the study's limitations, and outlines a future research agenda for cross-disciplinary research.

2. Literature Review

2.1 Theoretical Foundations of Sustainable Entrepreneurial Intentions (SEI)

Sustainable entrepreneurial intentions (SEI) refer to an individual's conscious and future-oriented commitment to launch ventures that pursue not only economic returns but also social and environmental value. Grounded in the Theory of Planned Behaviour (TPB), SEI has been theorised as a multidimensional construct encompassing ecological concern, ethical obligation, and perceived behavioural control (Peng et al., 2021). Compared to general entrepreneurial intention, SEI places greater emphasis on pro-social motivations and environmental sustainability as core behavioural drivers.

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In the last ten years, the literature has moved beyond cognitive antecedents centred on self-efficacy and personal attitudes and has started shifting toward more systemic, stakeholder-involved perspectives (Anser et al., 2024). Recent research highlights the roles of ecological mindsets, social norms, and sustainability narratives in shaping SEI. This transformation reflects broader socio-environmental changes and calls for entrepreneurs to serve as agents of sustainable development. The education sector is another key driving force behind sustainability-oriented entrepreneurship, as universities increasingly incorporate sustainability values into entrepreneurial education (Lopez-Leyva et al., 2022). The blended method of teaching, involving the combination of innovation, behavioural science, and environmental ethics, has proved its effectiveness in the development of sustainable intentions among the students. In the higher education sector, the augmentation of simulations and experience-based learning models with AI, in turn, complements SEI through aligning the inspirations of the students with green innovativeness (Juanda et al., 2024).

However, the knowledge base remains fragmented. Some research streams emphasise affective and motivational factors, while others focus on institutional and policy-level determinants (Goel et al., 2024). These silos lack integrative modelling and often ignore longitudinal dynamics in intention development. In conclusion, SEI research has diversified in scope and theoretical grounding, yet still requires deeper conceptual coherence, particularly regarding technology-mediated intention formation.

2.2 Artificial Intelligence as a Cognitive and Strategic Enabler of SEI

Artificial intelligence is increasingly recognised as a transformative force in entrepreneurship, enabling data-driven forecasting, resource efficiency, and low-carbon innovation (Jose & Muhammed, 2024). Entrepreneurs are using AI tools to anticipate market dynamics, design eco-conscious products, and streamline decision-making, thereby aligning business goals with sustainability objectives.

At the cognitive level, AI has been shown to enhance opportunity recognition, reduce uncertainty, and simulate complex entrepreneurial scenarios (Usman et al., 2024). Generative AI systems such as ChatGPT are now framed as cognitive companions that support entrepreneurial ideation, reflection, and self-efficacy. The intention formation literature discusses methods to facilitate cognition processes in the making of decisions. Modern interventions often employ real-time feedback systems that minimise cognitive load in complex decision scenarios (Sarumi, 2024).

Recent studies note that top-down mechanisms, such as green leadership and institutional AI policies, are central to leveraging AI for sustainable innovation (Zhao & Gómez, 2023). However, there are also still significant barriers, particularly for smaller and medium-sized businesses (SMEs), such as insufficient technical capacity, a lack of explainability, data bias persistence, and the general accountable implementation of AI. Due to such ethical constraints, the realisation of the sustainable, innovative, and human-AI interaction principles requires governance frameworks that integrate these three principles.

Recent literature suggests that the perceived moral integrity of AI is beginning to shape entrepreneurial intention. Empirical evidence shows that entrepreneurs are more likely to adopt AI into their sustainable enterprises when they trust the tool's fairness, transparency, and accountability (Klarin et al., 2024). This marks a shift from viewing AI as a value-neutral tool to perceiving it as a socially situated agent in the development of entrepreneurial motivation. Consequently, AI is transforming sustainable entrepreneurial innovation not only by enhancing capabilities but also by introducing new ethical, psychological, and institutional dimensions to the entrepreneurial process.

2.3 Bridging SEI and AI: Insights from Bibliometric Research and Research Gaps

In the recent bibliometric studies, the emerging intersection of entrepreneurship and AI is characterised as a growing focal point currently active in the field, and research in this intersection covers exploration of the field of business models based on AI, digital transformation, and innovation with sustainability (Wadhwa & Bansal, 2024). Co-citation, keyword co-occurrence, and bibliographic coupling methods have been used to trace thematic clusters and intellectual foundations in this emerging field (Goel et al., 2024).

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Despite this growth, most bibliometric analyses treat AI, entrepreneurship, and sustainability as parallel rather than integrated streams (Dasawat & Sharma, 2023). As a result, critical questions remain unanswered: How do AI technologies alter the cognitive pathways of SEI? What ethical tensions arise when AI mediates sustainable entrepreneurial intent? Which collaborative networks and institutions are shaping this new interdisciplinary domain?

The literature also reveals under-theorised constructs such as digital sustainability, namely the idea that AI should not only improve efficiency but also contribute to systemic transformation aligned with the UN SDGs (Yang & Lee, 2024). Few studies explore how AI amplifies or constrains sustainability salience, particularly in emerging economies where digital infrastructure is uneven.

Theoretical integration is urgently needed. Existing models like TPB, stakeholder theory, and institutional logic fail to account for AI's dynamic, context-sensitive role. Scholars have called for new frameworks such as the AI-PEN (Prospecting and Establishing Nexus) model and human–AI collaboration theory to map these evolving patterns (Giuggioli & Pellegrini, 2022). These models can potentially bridge intention, cognition, ethics, and technology into a unified framework. In conclusion, the bibliometric landscape confirms a growing scholarly interest in SEI and AI convergence but highlights a lack of theoretical integration and contextual nuance, a gap this study seeks to address.

3. Methodology

3.1 Research Design

This study employs a bibliometric analysis to map the intellectual landscape and thematic evolution at the intersection of sustainable entrepreneurial intentions (SEI) and artificial intelligence (AI). Bibliometric techniques offer a systematic and replicable approach to evaluate scholarly output, detect influential contributions, and uncover emerging research trends in complex and interdisciplinary fields.

To this end, we adopted two complementary analytical methods: (1) co-citation analysis, which identifies the intellectual structure of the field by examining documents frequently cited together; (2) keyword co-occurrence analysis, which reveals the conceptual structure by detecting co-appearing terms and thematic clusters. The studies identified in this paper were analysed using VOSviewer, a software application that transforms bibliometric data into visual networks, enabling empirical analysis of intellectual convergence and ideological change.

In analysing the academic discourse of AI-powered sustainable entrepreneurship, we rely on bibliometric network maps and clusters obtained on the basis of VOSviewer-created citation networks. VOSviewer enables the creation of co-authorship, co-citation, and co-occurrence networks and makes them available in the form of a graphical illustration, which can be compared over temporal or disciplinary regions. This type of visualisation will allow a more empirical exploration of the transdisciplinary composition of such fields and will explain where existing studies could be directed better (Orduña-Malea & Costas, 2021; Ding & Yang, 2022).

3.2 Data Collection

The research uses Scopus as the primary data source because the database provides a broad collection of peer-reviewed literature encompassing entrepreneurship, artificial intelligence, and sustainability. Scopus is a credible indexing service with extensive bibliographic records, making it well-suited for large-scale bibliometric research (Baas et al., 2020). Combining journal articles, conference proceedings, and a variety of scholarly articles, Scopus becomes a valid tool in following intellectual turnover and forming themes in a cross-disciplinary scope, specifically artificial intelligence and sustainable entrepreneurship.

To ensure the inclusion of high-quality and relevant publications, we developed a structured search strategy. Through an iterative process, we identified relevant keywords spanning entrepreneurship or innovation, artificial intelligence, and sustainability, and formulated the following query:

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TITLE-ABS-KEY *("entrepreneurial intention" OR "entrepreneurship" OR "innovation") AND TITLE-ABS-KEY ("artificial intelligence" OR "AI" OR "machine learning" OR "deep learning" OR "big data") AND TITLE-ABS-KEY ("sustainability" OR "green" OR "eco-friendly" OR "green economy" OR "environmental sustainability" OR "CSR" OR "corporate responsibility") AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO(DOCTYPE, "ar") AND (LIMIT-TO(LANGUAGE, "English") AND (LIMIT-TO(SRCTYPE, "j") AND (LIMIT-TO(PUBSTAGE, "final").*

The initial search yielded 4,968 documents. After narrowing the parameters to publication years between 2015 and 2025 and limiting the dataset to peer-reviewed journal articles in the English language that were finalised for publication, the dataset consisted of 1,855 articles, as shown in Table 1.

Table 1. Data Collection Process and Search Strategy in Scopus Summary

Step	Description	Details / Parameters	Outcome
1. Data Source Selection	Primary database chosen	Scopus covers peer-reviewed scholarly materials in entrepreneurship, AI, and sustainability; it is a credible indexing service with extensive bibliographic records (Baas et al., 2020)	Suitable for large-scale bibliometric research
2. Rationale	Reason for selection	Cross-disciplinary coverage (entrepreneurship, AI, sustainability); includes journal articles, conference proceedings; supports tracking intellectual turnover and theme formation.	Valid for AI & sustainable entrepreneurship research
3. Search String Development	Keywords and Boolean operators	TITLE-ABS-KEY("entrepreneurial intention*" OR "entrepreneurship" OR "innovation") AND TITLE-ABS-KEY("artificial intelligence" OR "AI" OR "machine learning" OR "deep learning" OR "big data") AND TITLE-ABS-KEY("sustainability" OR "green" OR "eco-friendly" OR "green economy" OR "environmental sustainability" OR "CSR" OR "corporate responsibility")	Captures entrepreneurship/innovation, AI technologies, and sustainability topics
4. Initial Query Parameters	Additional filters	PUBYEAR > 2004 AND PUBYEAR < 2026; document type: "ar"; language: English; source type: journal; publication stage: final	**Initial results:** 4,968 documents
5. Refinement Criteria	Narrowing search	Publication years: 2015–2025; peer-reviewed journal articles; English language; finalized publications only	**Final dataset:** 1,855 articles

Note: Retrieved the data in Scopus; search done using the given Boolean search with filtering on year, language, document type, and publication stage.

3.3 Data Analysis

The current analysis relies on VOSviewer 1.6.20, a software program for constructing and querying bibliometric networks. Based on a mixture of citation data, co-occurring keywords, and co-citation, the software creates a detailed but informative visualisation of a disciplinary landscape (Kartal & Yeşilyurt, 2024). Two primary forms of analysis were employed in the study: co-citation analysis and keyword co-occurrence analysis.

Co-citation analysis helped to identify highly influential publications by capturing documents that are frequently cited together. The co-cited papers identify citation pairs, which may suggest shared theoretical underpinnings or methodological approaches. They are therefore valuable for revealing the major intellectual clusters in the domain of AI and sustainable entrepreneurship research. Co-citation analysis also displays the predominant papers, authors, and sources that shape and continue to shape an academic discourse over time (Thayyib et al., 2023). In contrast, keyword co-occurrence analysis maps thematic linkages by identifying keywords that co-occur in the same documents. The keyword co-occurrence analysis enables the identification of emerging topics, prevalent themes, and interdisciplinary links that occur throughout the dataset as a whole.

To capture the temporal dynamics of research evolution, we employed overlay visualisation techniques. These highlight the chronological emergence of themes, showing how scholarly attention has shifted from general sustainability concepts to more nuanced topics such as responsible AI governance, AI-augmented intention models, and ethics-oriented entrepreneurship education. All bibliometric indicators, such as citation counts, link strength, and cluster density, were analysed to interpret the structural and thematic composition of the field.

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Together, these analyses provide a multidimensional portrayal of how AI and SEI research domains are converging, offering both retrospective insights and forward-looking trajectories.

4. Results and Discussion

4.1 Trend Analysis

Figure 1 illustrates the yearly publication distribution of sustainable entrepreneurship, artificial intelligence (AI), and innovation. The trend indicates a growing academic interest in this multidisciplinary field, particularly since 2020. From 2015 to 2018, the annual publication count fluctuated below 50 documents. The low output confirms that scholarship in AI-powered sustainable entrepreneurship was in its infancy. In 2019, an incremental upward rise began. The annual count of relevant publications began to rise in tandem with the overall proliferation of AI and the increasing emphasis on sustainability-based innovation. The years 2020 and 2021 saw a substantial increase, with document count nearly doubling. As a result, scholars began to acknowledge the role of AI technology in transforming entrepreneurial ecosystems toward sustainability.

The most significant acceleration occurred between 2022 and 2023. In 2022, roughly 230 articles were published. With a meteoric rise in 2023, over 600 publications were produced, the highest figure in the entire dataset. This surge was occurring alongside increasing global attention to digital sustainability, climate entrepreneurship, and the responsible integration of AI into business models. Scholars have begun to explore how knowledge and intelligent systems can maximise the sustainable purpose of business operations, inform sustainable startup businesses, and align entrepreneurial behaviour with the UN Sustainable Development Goals (SDGs) (Bickley et al., 2025).

The evidence suggests a slight decrease anticipated in 2025; this is likely a consequence of the data collection cutoff in May 2025, rather than a sample of diminished academic interest. Additionally, the complete year was not captured in the data collection, and the appearance should be taken as transitory, not an indication of falling interest among scholars. In conclusion, the trend analysis suggests that AI-powered sustainable entrepreneurship has rapidly evolved into a legitimate and expanding area of research. The increasingly abundant publication profile over the years reflects growing global concerns about ecological responsibility, technology disruption, and precise innovation. The scholarly presence is expected to continue expanding in the coming years, alongside the further integration of AI into green business practices and the rise of purpose-oriented entrepreneurship.

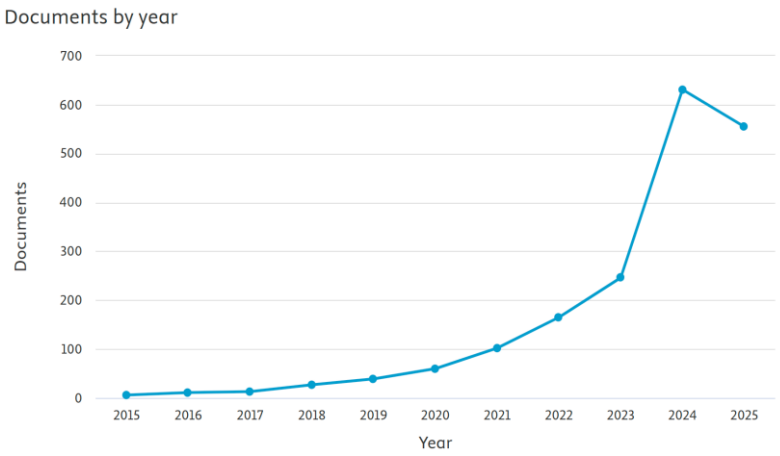


Figure 1. Number of publications and citations between 2015 and 2025.
Source: Scopus

4.2 Citation Analysis

We utilised co-citation analysis to explore the intellectual foundation of sustainable entrepreneurial intentions (SEI) in the context of artificial intelligence (AI), mapping the structural evolution of the academic literature and identifying important works on sustainable entrepreneurship. Co-citation analysis is particularly suitable

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for emerging interdisciplinary fields, such as SEI and AI, as it systematically reveals the underlying knowledge base, key themes, and academic convergence patterns (Ferreira & Ferreira, 2024).

The Scopus database was selected as the data source due to its extensive coverage of high-impact journals, rigorous curation, and suitability for advanced co-citation clustering using tools like VOSviewer and Biblioshiny (Manoharan et al., 2024). Of 11,959 cited references, 57 exceeded the citation threshold of 9, forming four major knowledge clusters. To identify the most influential intellectual anchors within the co-citation landscape, the top 10 references with the highest total link strength are summarised in Table 2. These clusters reflect the theoretical scaffolding of SEI research, spanning strategic sustainability, entrepreneurial psychology, AI policy frameworks, and methodological foundations. Figure 2 presents the thematic co-citation network generated using VOSviewer. It visually illustrates the four major intellectual clusters that emerged from the 57 high-frequency co-cited references.

Table 2. Top 10 Cited References by Total Link Strength

Cited Reference	Citations	Total Link Strength
(European Commission. Directorate General for Communications Networks, Content and Technology, 2021)	14	532
(Act, 2020)	38	532
(El-Kassar & Singh, 2019)	18	87
(Fornell & Larcker, 1981)	20	82
(Waqas et al., 2021)	13	82
(Bag et al., 2020)	16	78
(Al-Khatib, 2022)	12	75
(Hair et al., 2019)	18	72
(Hart, 1995)	14	65
(Barney, 1991)	23	64

Note. Scopus data (2015–2025); total link strength determines the level of co-citation connectivity between a given reference and others within the network, calculated by using VOSviewer.

Cluster 1. Strategic Sustainability and Entrepreneurial Innovation

This cluster highlights the intersection between sustainable business strategies and entrepreneurial innovation, particularly in AI-driven contexts. Research in this group emphasises the integration of sustainability goals into business models, with green innovation, dynamic capabilities, and triple-bottom-line performance as recurring themes (Anand et al., 2021; Islam & Can, 2024). These studies collectively show that sustainability is increasingly operationalised as a strategic resource that reinforces entrepreneurial competitiveness, rather than a passive compliance mechanism. In addition, recent efforts indicate that the use of analytics facilitated by AI enables companies to have a more predictive understanding of their environmental effects, align their product development with concepts of the circular economy, and detect new markets that can be approached with offers of sustainable products and services (Anand et al., 2021). Such an association of predictive intelligence and eco-innovation has a proactive tendency, as sustainability is incorporated into many decision-making steps in ideation to commercialisation, it will improve resilience and market differentiation (Islam & Can, 2024).

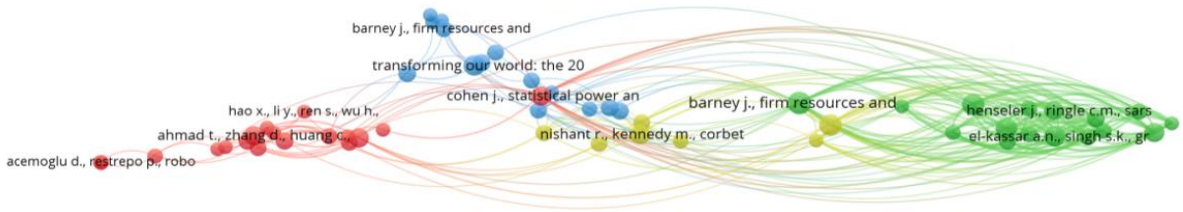


Figure 2. Thematic Co-citation Network of AI and Sustainable Entrepreneurship (VOSviewer)

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Cluster 2. Entrepreneurial Psychology and Intentional Behaviour
This cluster includes psychological and behavioural theories that explain how individuals form sustainable entrepreneurial intentions. The existing frameworks include the Theory of Planned Behaviour, entrepreneurial cognition, and digital self-efficacy; however, the more recent additions include algorithmic trust, AI ethics, and moral identity (Blanco-González-Tejero et al., 2023; Rahman et al., 2024), and this demonstrates an overall transition from general models of intention theories to a more digitally embedded psychological framework.

More specifically, the empirical evidence refers to the moderating effect of AI-supported feedback systems, like the customised personalised learning services and real-time environmental data analysis dashboards, on increasing both self-efficacy and commitment to sustainable entrepreneurship (Blanco-González-Tejero et al., 2023). These tools contribute to bridging the intention-behaviour gap through unending reinforcement and performance monitoring that motivates an actor to continue with the effort of exploring eco-innovative ventures despite any uncertainty (Rahman et al., 2024).

Cluster 3. Institutional Frameworks and AI Governance
This cluster is concerned with macro-influences, such as institutional policies and intermediary regulations that enable sustainable entrepreneurship (SE) as they relate to rest-of-world policies, digital infrastructure policies, and practices. Some of the prominent literature looks at frameworks, including the European Union Digital Finance Strategy and innovation ecosystems aligned with the UN SDGs (Kharchuk et al., 2024; Miah et al., 2024). These studies argue that institutional legitimacy and 'digital readiness' are important precursors to SEI development.

Moreover, international comparisons show that countries such as Denmark and Germany, with the coordinated AI regulation incorporating ethics, transparency criteria, and sustainability incentives, have more chances to scale the green-tech startups fast (Kharchuk et al., 2024; Miah et al., 2024). This synergy between explicit regulatory signals and the possibility to monitor compliance with them with the help of AI technologies decreases barriers to entry, induces confidence in investors, and enables a faster speed of diffusion of sustainable innovations across national boundaries.

Cluster 4. Methodological Rigour and Bibliometric Tools
The cluster showcases some advancements in methods used in SEI studies, such as the use of VOSviewer and Biblioshiny, bibliometric platforms that allow researchers to visualise and map out knowledge structures. The publications went even further by following standardisation on writing, stating validity, reproducibility, and ultimately mapping precisely what is being done through network-based visual analytics (Kaushik & Dangwal, 2025; Perwitasari et al., 2023). In general, if applications of these types of studies become more widespread, the academic field can build an empirical base and gain further legitimacy as a study area. Also, parallel to the above, scholars are employing the methods of natural language processing (NLP), aiming to integrate and connect bibliometric methods and AI-based topic models to discover emergent trends and identify hidden research themes. This analytical convergence is superior as it facilitates an examination of existing gaps between concepts and disciplines, identification of the frameworks of cross-disciplinary bridges, and strengths in search areas in a given field of sustainable entrepreneurship motivated by AI (El-Kassar & Singh, 2019).

4.3 Keyword Analysis
To investigate the thematic structure, conceptual framework, and intellectual subdomains of sustainable entrepreneurial intentions within the context of artificial intelligence, the study used keyword co-occurrence analysis. Based on 62 high-frequency keywords (occurrence threshold $\geqslant$ 36), four distinct clusters were identified (see Figure 3).

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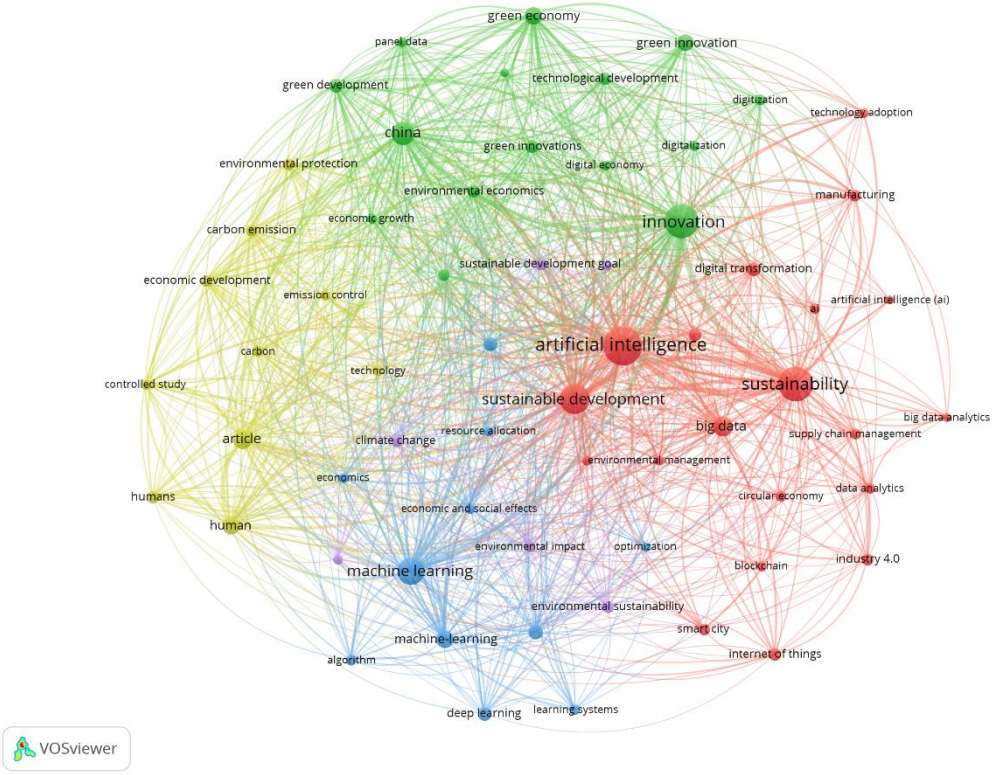


Figure 3. Thematic Keyword Co-Occurrence Network (VOSviewer).

The keywords and phrases ranked using total link strength are listed in Table 3. There are numerous thematic motifs related to the keyword themes; however, a few that stand out are artificial intelligence, entrepreneurial intention, sustainability, and innovation, indicating a lesser reliance on technology and its greater purpose and symbolising cognitive values that interrelate thematic areas in academia.

Table 3. Top 10 Keywords by Total Link Strength

Keyword	Occurrences	Total Link Strength
artificial intelligence	610	2117
innovation	478	2093
sustainable development	367	1721
sustainability	510	1620
China	231	1345
machine learning	312	1251
human	132	809
green economy	124	803
economic development	64	503

Note: Scopus (2015–2025); data, link strength in the text box refers to the connectivity (co-occurrence of the keywords in the VOSviewer visualisation).

Cluster 1. AI-Enhanced Entrepreneurial Intentions and Innovation Systems

Cluster 1 (22 items) focuses on the interaction between artificial intelligence (AI) and entrepreneurial intention, as well as how AI-enabled technologies are changing innovation processes, entrepreneurial ecosystems, and individual opportunity recognition. The leading keywords in this cluster are artificial intelligence, entrepreneurial intention, innovation, digital transformation, and technology acceptance.

AI is widely recognised as more than a tool but a cognitive partner within the entrepreneurial process, enabling real-time feedback, opportunity confirmation, and decision-making amid uncertainty (Townsend & Hunt, 2019). By framing generative AI tools such as ChatGPT and GPT-5 as cognitive companions, novice

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entrepreneurs can not only alleviate cognitive overload but also reinvigorate their opportunity recognition, business model ideation, and innovation strategies. Their potential as cognitive companions means that their capacity to inform a multitude of decisions, particularly during the uncertainty of striving to be an entrepreneur, is undoubtedly promising (Cimino et al., 2024; Gupta & Yang, 2024).

This cluster suggests a shift in paradigm not only in how we think about entrepreneurial intention but also in how entrepreneurial cognition has traditionally been framed, which originated in individual intention shaped by background traits, and how this intention has transformed into an opportunity evaluation mediated by technology and digitally enhanced cognition.

Cluster 2. Sustainability Values, Motivation, and Psychological Mechanisms
Cluster 2 (21 items) examines the motivational, attitudinal, and psychological bases of sustainable entrepreneurship, emphasising the influence of pro-environmental values, sustainability orientation, and perceived behavioural control on entrepreneurial intent. Terminology emphasised in this cluster includes sustainability, motivation, behaviour, entrepreneurship education, and the theory of planned behaviour.

Numerous studies have established that a person's values and sense of moral obligation towards the environment are among the most robust antecedents to entrepreneurial intention with youth, especially university students (Kazmi et al., 2019; Baber, 2024; Zhang et al., 2024). The research has shown that youth motivation for green entrepreneurship is heightened when contextualised in an ecological framework or mindset and communicated effectively via digital technologies with sustainability narratives (Uvarova et al., 2021). This cluster affirmed the role of personal agency and moral cognition in social entrepreneurship, which is typically involved in sustainable entrepreneurship, and was digitally supported through AI-aided learning environments and teaching.

Cluster 3. Entrepreneurial Education, Learning Systems, and Youth Engagement
Cluster 3 (19 items) focuses on educational and cognitive growth paths related to entrepreneurial demonstrated behaviours, with keywords reflecting this, including entrepreneurship education, students, learning, intention, and behavioural outcomes. Recent research published in top-tier journals has shown that embedding AI technology and sustainability content into entrepreneurship curricula substantially increases students' entrepreneurial self-efficacy and intention.

AI technologies, including recommender systems, simulations, and adaptive learning, enabled students to align their entrepreneurial ideas with their interests and aspirations (António Porfírio et al., 2023; Zulfiqar et al., 2025). Increasingly, AI is thought of as a cognitive partner in entrepreneurship learning systems (Shepherd & Majchrzak, 2022). Cluster 3 indicates the emerging roles of formal education, experiential learning, and adaptive learning systems for the future generation of entrepreneurs who adopt a sustainable mindset, representing a shift in consciousness within our social systems.

Cluster 4. Ethics, Perceptions, and AI Legitimacy in Sustainable Entrepreneurship
Cluster 4 (17 items) includes ethical, perceptual, and legitimate concerns surrounding the entrepreneurship ecosystems of AI. Keywords include ethics, trust, perceptions, the technology acceptance model, and responsible AI. Trust and ethical perceptions of AI are increasingly recognised as a crucial moderating factor in the adoption of sustainable entrepreneurship using AI. Trust is not only an attribute of a technology but also a social construct that is influenced by social constructs of fairness, transparency, and accountability.

Reviews of empirical studies in the literature found that ethical concerns are significant in shaping trust in both the public and entrepreneurial worlds in the AI technologies affecting their legitimacy and responsible use (David et al., 2024; Ryan, 2020). Professional and organisational value-based ethical AI implementation frameworks establish both immediate and long-term legitimacy within society (Cumming et al., 2024; Klarin et al., 2024). This cluster highlights a growing recognition that technological tools must be embedded in ethical frameworks to maintain legitimacy, especially when applied to ecologically and socially sensitive entrepreneurship goals.

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5.1 Theoretical Implications

This study enriches the theoretical discourse on entrepreneurship by advancing emerging perspectives that integrate artificial intelligence (AI) with entrepreneurial intention, cognition, and ethics. Specifically, our findings substantiate a paradigm shift: from static trait-based models of entrepreneurial behaviour to dynamic, technology-mediated cognitive frameworks, aligning with recent calls to reconceptualise entrepreneurial intention as an interactional outcome shaped by AI-enhanced environments (Jeremiah, 2025). We contribute to the technology acceptance and planned behaviour literature by demonstrating that generative AI tools do not merely assist in processing information but actively shape entrepreneurial self-efficacy, digital opportunity recognition, and entrepreneurial agency. These findings expand the Theory of Planned Behaviour by showing that perceived behavioural control is increasingly co-constructed with AI-based scaffolding systems that augment the entrepreneur's cognitive evaluation of feasibility and desirability (Duong et al., 2024; Duong & Nguyen, 2024).

Further, the research contributes to sustainability-oriented entrepreneurship theories by introducing AI-curated digital ecologies as transformative mediators of moral cognition and value salience. Prior studies highlight pro-environmental value orientation as a key driver of entrepreneurial intention (Liao et al., 2022). We extend this by theorising that algorithmic narratives and data-driven scenario modelling within AI-enhanced systems elevate sustainability salience and activate moral agency through affective feedback loops.

In parallel, our work revisits the foundations of entrepreneurship education by repositioning AI from a passive pedagogical assistant to an active cognitive partner. This aligns with constructivist models while expanding them to include human–AI collaborative knowledge construction. Generative AI facilitates immersive, adaptive learning trajectories that shape entrepreneurial cognition and foster autonomous knowledge construction (Parker et al., 2024; Guan et al., 2025).

Finally, we provide a critical theoretical extension: we propose that ethical trust and perceived legitimacy of AI systems are not external adoption drivers but internal antecedents of entrepreneurial intention itself. An intention to engage with AI as part of entrepreneurial pursuits is contingent on perceiving the algorithmic implications to be ethically fair, explainable, and emotionally aligned. We suggest an extension of the behavioural intention (BI) models to recognise trust in AI as a first-order cognitive process (Graves, 2023; Wiese et al., 2023). In doing so, we provide a refined theoretical lens for understanding, particularly, the formation of intention in the context of AI-mediated, sustainability-focused entrepreneurial activity.

5.2 Practical Implications

The implications of this research provide meaningful, actionable recommendations and insights for a variety of constituents engaged at the intersections of generative AI, entrepreneurship education, and sustainable innovation. For educators and institutions, this research provides an evidence-based rationale to incorporate generative AI tools (courses of engagement and learning) for entrepreneurship education, especially adaptive business simulators and AI feedback engines. These systems enhance linear coding mechanisms towards learner-driven environments that allow for individual, real-time scenario-based assessments of entrepreneurial cognition and sustainability-oriented problem legitimation, especially for novice entrepreneurs and university students (Mittal et al., 2024).

From a policy perspective, this research highlights the need for equitable digital infrastructure to facilitate and support the responsible integration of AI across entrepreneurial ecosystems. Policy objectives directly relate to the need for financial investments that improve equitable access, especially in impoverished regions and other underfunded communities, and the importance of national or institutional campaigns that promote AI literacy, encompassing not only fluency in technology but also ethical literacy (Yusuf et al., 2024). Policies designed for education or entrepreneurship training interventions must provide their users with clear frameworks for deciding on accountability, fairness, and explainability of how they use large, mounted AI systems, thereby reducing the risk of inadvertently widening existing inequalities (Wei et al., 2025).

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For designers and technology developers, an AI system will need to be ethical, transparent, and adaptable, facilitating ESG (Environment, Social, Governance) principles that are situationally contextualised from what the entrepreneurial learner can and cannot do for actionable comfort. Ideally, the user interface could accommodate ethical filters and psychological profiling functions, as well as feedback on one's learning process, while taking into account the parameters of sustainability goals and the uncertainty of possible entrepreneurial success. There may be practice-based opportunities for features such as federated learning or differential privacy on data-sensitive platforms used for developing startups or exploring unknown, future entrepreneurial opportunities (Omran Almagrabi & Khan, 2025).

For students and future entrepreneurs, this research provides logical support for the evidence that generative AI systems can serve as cognitive amplifiers of existing confidence, opportunities, and iterations. Immersive, context-aware real-time simulations, when embedded within ethically bounded business modelling environments, offer learners a safe yet cognitively authentic space to navigate risk, confront failure, and grapple with ethical dilemmas before engaging in real-world managerial decision-making. However, generative AI learning engagements build even more immersive configurations of course navigation and self-regulated, unique contexts of engagement by learning to reflect on how aligned they are with their entrepreneurial intent, ecological, or social priorities when they do not have to report their learning (Ahmed et al., 2024).

In closing, the action implications of the knowledge generated by this research are clear. As educators, developers, and policymakers, we need to collaborate and coordinate to enhance the function of the systems we build from generative AI that, at scale, does decision-making for us and is both efficient and ethically sustainable. Generative AI has the potential to build a lot of possibilities, and to do so fairly, we need to be committed to a collectively designed system guided by regulators, educational developers, ethical designers, and the users themselves.

6. Conclusion, Limitations, and Future Research Direction

6.1 Conclusion

This research provides a holistic understanding of how generative artificial intelligence (AI) will influence our definition of intention concerning entrepreneurship, our values associated with sustainability, the establishment of educational ecosystems, and people's ethical constructs. We employed a bibliometric and cluster analysis to understand and explore four distinct yet interrelated domains: generative AI-driven cognitive aspects of entrepreneurship, sustainability-based value creation, the use of AI in pedagogical choice and design, and the ethical legitimacy of AI adoption in technology-mediated ventures.

The results illustrate that generative AI is more than an adjunct; rather, it is the cognitive co-agent in the entrepreneurial ecosystem. Significantly, it changes the underlying constructs of the intentions of opportunity recognition, self-efficacy, and how people will see controls on behaviour, even in youth and in sustainability-based forms of entrepreneurship (Duong et al., 2024; Jeremiah, 2025). The study also highlighted the importance of trust, explainability, and fairness in people's acceptance of AI's relevance in the entrepreneurial domain and called upon researchers to start rethinking ethically embedded cognitive frameworks (Graves, 2023).

6.2 Limitations

Despite its contributions, the study carries several limitations. First, the bibliometric data were exclusively sourced from Scopus, which may exclude frontier research in early-stage journals or region-specific studies. Research has emphasised the need to triangulate with Web of Science and domain-specific repositories to avoid potential bias in innovation studies across global entrepreneurship systems (Wang & Zhang, 2024). Second, future studies should operationalise ethical AI frameworks and integrate fairness audits and governance protocols into empirical models. Using explainable artificial intelligence (XAI) in entrepreneurship platforms can cast light on how algorithmic approaches diversify conceptions of adoption and legitimacy (Weidener & Fischer, 2024).

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Future studies must thus be focused on technological innovation of the implementation of artificial intelligence (AI) and generative artificial intelligence (Gen AI) in regard to education, identification of opportunities, and ethical simulation through deep learning. The combination of Structural Equation Modelling (SEM) and Artificial Neural Network (ANN) brings knowledge regarding AI and how it is anthropomorphised and regarded as intelligent. Furthermore, an interesting relationship is observed between the adoption of responsible technologies and social sustainability, which leads to the apparent lack of emotional adaptive architecture (Al-Emran et al., 2024).

6.3 Future Research Directions

Building on our insights and limitations, we suggest four promising directions for future research. First, longitudinal studies are crucial for evaluating the sustained impact of generative AI on entrepreneurial performance, digital strategy alignment, and sustainability awareness. Evidence from education-centred entrepreneurship ecosystems suggests that generative AI has a significant impact on task performance, perceived tool alignment, and entrepreneurial success over time (Marchena Sekli & Portuguez-Castro, 2025). Second, the methodological reliance on co-citation and cluster analysis emphasises macro-level knowledge structures but does not capture in-depth contextual or qualitative dynamics of AI use in entrepreneurship. The temporal cutoff also restricts the capture of rapidly emerging trends in generative AI models, such as GPT-5 or multimodal platforms, which are likely to further reshape the ecosystem (Wiese et al., 2023). Finally, while we conceptually address ethical implications—e.g., bias, transparency, and fairness—our study does not empirically test how these factors impact AI adoption across diverse socio-cultural or institutional contexts. Such omission limits practical generalisation and calls for more granular, cross-sectional, and mixed-method investigations.

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INTEGRATING IFRS 15 INTO BUDGETING AND COST ESTIMATION FOR SOFTWARE COMPANIES

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Abstract. In today's digital economy, software projects, including customized development, software-as-a-service arrangements, and usage-based components, require financial planning mechanisms that ensure coherence between technical execution and financial reporting. Sustainability-oriented budgeting refers to a planning process that promotes transparency, financial stability, and long-term resilience. To be applied effectively in the software industry, it requires an explicit connection between cost estimation and the recognition of revenues in accordance with International Financial Reporting Standard 15. This operational link is essential, as technical project progress, mixed contract structures (licensing, customization, maintenance, usage), and the presence of variable consideration can generate discrepancies between managerial execution and accounting recognition. The paper develops and validates an integrated operational framework that connects cost estimation with revenue recognition under International Financial Reporting Standard 15, with the aim of supporting transparent and resilient budgeting in software projects involving variable consideration, such as usage-based royalties. The model addresses both cost-estimation challenges, driven by iterative development cycles, requirement changes, and resource intensity, and the difficulties associated with revenue recognition, especially in projects with progressive deliveries and compound pricing structures. The research methodology combines a bibliometric synthesis of recent literature with an in-depth case study of a two-year commercial software contract that includes licensing, customization, maintenance, and usage-based royalties. The results show that aligning cost estimation with revenue recognition reduces forecasting errors, improves execution discipline, and strengthens financial resilience, keeping project performance within stable limits even under varying user-consumption scenarios. The contribution of the study is threefold. First, it proposes a replicable operational framework that connects budgeting with financial reporting. Second, it provides empirical evidence based on a real contract from the software industry. Third, it formulates managerial and regulatory implications concerning transparency, internal control, and reporting quality in software projects.

Keywords: sustainability-oriented budgeting; software development; IFRS 15; cost estimation; variable consideration; financial sustainability

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JEL Classifications: M41, M11, M48, L86, O32, Q56

1. Introduction

Amid the accelerated expansion of the digital economy, software development has become a pillar of organizational competitiveness, where financial discipline and the need to strengthen long-term resilience increasingly shape managerial decision-making. Cost estimation and revenue recognition are essential mechanisms of budgeting; however, in practice, they are often approached in a fragmented and judgment-based

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manner, which reduces the accuracy of projections and weakens the usefulness of information for managers and stakeholders. In this context, a coherent operational framework is needed to explicitly link cost assumptions to revenue trajectories recognized in accordance with international standards, within a budgeting logic oriented toward transparency and financial sustainability.

The specialized literature reveals a persistent gap between theoretical models and their practical application in the field of information technology, where project customization, iterative development cycles, and rapidly changing user requirements amplify the volatility of financial indicators. Under these conditions, both cost structuring and the timing of revenue recognition are subject to significant uncertainty, which explains frequent deviations from budgeted values and uneven performance reported in the industry (Nicholas și Steyn, 2020; Venkataraman și Pinto, 2023; Kerzner, 2025). Although existing studies provide solid conceptual foundations, practical guidance on how to operationally integrate cost estimation and revenue recognition into a unified framework remains limited, particularly in software environments characterized by progressive deliveries and variable pricing models.

The implementation of IFRS 15 underscores the need for enhanced methodological rigor. The identification of performance obligations, the allocation of the transaction price, and the progressive recognition of revenue directly influence the budgeting process and the monitoring of execution. Integrating the standard's requirements into financial planning mechanisms requires careful alignment between cost assumptions and revenue trajectories, in order to avoid inconsistencies between the project's economic model and the way performance is reported (Jieri, 2023; Onie et al., 2023; Cojocaru et al., 2025). Nevertheless, the literature does not provide an operational model that explicitly connects the principles of the standard with budgeting practices in software projectsojects.

In parallel, budgeting must reflect modern performance criteria that go beyond traditional project indicators such as cost, schedule, and immediate profitability. Long-term financial evaluation, efficient resource utilization, and economic stability become essential dimensions of financial sustainability. Although concepts such as responsible software development and resilience-oriented budgeting are increasingly discussed, they are rarely translated into measurable and verifiable procedures capable of ensuring traceability of decisions and deviations relative to financial objectives. From the perspective of stakeholder transparency requirements, software companies are expected to demonstrate both the economic rationale of their budgets and the way these budgets support stability and continuity.

Recent studies also emphasise that budgeting practices in technology-intensive environments must account for long-term financial resilience and disciplined resource use, rather than focusing solely on short-term cost and profit indicators (Pantović et al., 2024; Soongpol et al., 2024).

Despite these developments, the literature has not examined how managerial budgeting techniques, revenue recognition under International Financial Reporting Standard 15, and long-term financial performance principles can be integrated into a single operational framework applicable to the software domain. To address this gap, the present study formulates the following research questions:
RQ1: How can cost estimation and IFRS 15 revenue recognition be operationally integrated into a sustainability-oriented budgeting model for software projects?
RQ2: To what extent does such an integrated model reduce forecasting errors and improve execution discipline?
RQ3: How does sustainability-oriented budgeting contribute to financial resilience in projects with variable consideration?

The purpose of this research is to develop an integrated operational model that supports sustainability-oriented budgeting through the alignment of cost estimation, IFRS 15 revenue recognition, and performance measurement. The novelty of the study lies in proposing a dual-flow framework-operational and financial-accounting-ensuring full cost–revenue traceability, IFRS consistency, and sustainability-driven performance evaluation. This approach advances the literature by addressing the triple alignment gap and by offering a replicable methodological tool suitable for software companies.

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The study provides three main contributions:

1. A replicable operational framework linking cost estimation, IFRS 15 revenue recognition, and sustainability-oriented budgeting.
2. Empirical evidence from a real two-year software contract, demonstrating improved accuracy and financial resilience.
3. Managerial and policy implications for enhancing transparency, internal control, and sustainability reporting in technology-intensive firms.

The remainder of this paper is structured as follows. Section 2 reviews the literature and theoretical background. Section 3 presents the research methodology. Section 4 reports and discusses the results, including the integrated operational model, case study evidence, performance indicators, sensitivity analysis, and hypotheses validation. Section 5 concludes with key implications and directions for future research.

2. Literature Review

The accumulated literature outlines a coherent diagnosis. There are significant contributions on cost estimation in software projects and, separately, solid analyses of revenue recognition under IFRS 15 logic, complemented by an emerging line of research dedicated to sustainable budgeting. However, an insufficiently explored area persists: the articulation of these three dimensions into a single operational framework, adapted to the specifics of software development and useful for decision-making in financial planning and reporting. Consequently, our approach explicitly starts from this gap and seeks to integrate cost estimation and revenue recognition, alongside relevant sustainability indicators, into a model that can be applied in practice.

The bibliometric analysis supports this positioning, being grounded in studies published between 2020 and 2025. The distribution of the most frequent terms indicates a convergence between project management, sustainability, and software specifics, signaling a transition from conceptual definitions to methodological operationalization (see Figure 1).

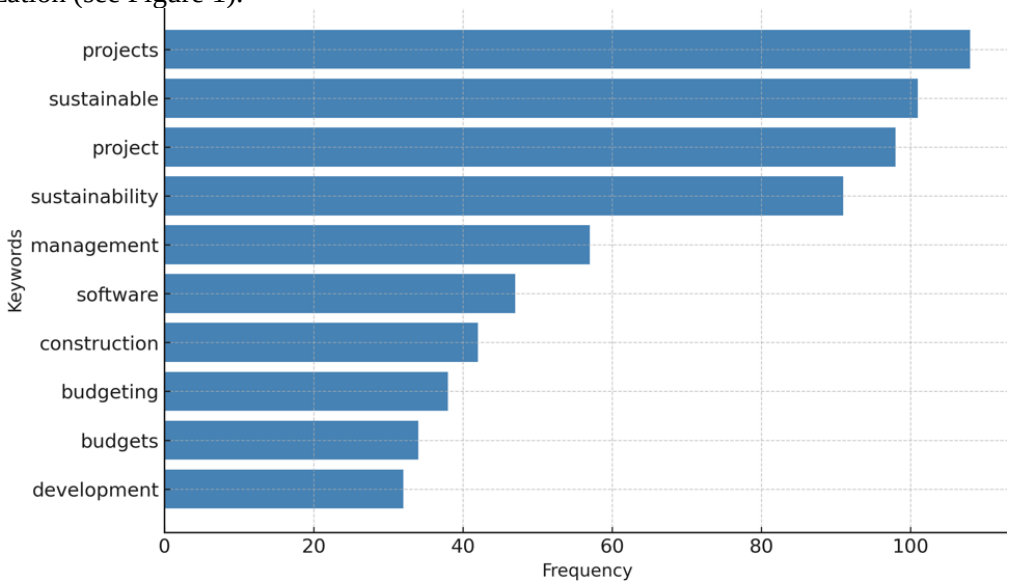


Figure 1. Top 10 most frequent keywords in studies on sustainable budgeting for software projects
Source: authors' own elaboration

Figure 1 presents the distribution of the ten most frequent keywords identified in the specialized literature on the sustainable budgeting of software projects. Dominant terms, such as projects, sustainable, project, and sustainability, indicate that the research core is built around the interdependence between the concept of sustainability and project management. This terminological concentration confirms the academic orientation towards integrating ecological and social responsibility within financial and organizational practices.

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The presence of the term management highlights that sustainable budgeting is analyzed not only as a financial tool but also as a mechanism for the strategic coordination of resources. The word software reflects the applicative specificity of the IT field, while the occurrence of the terms construction and budgeting suggests the transfer of established methodologies from other sectors, especially construction, to the information technology sector. At the same time, the presence of the terms budgets and development indicates an ongoing concern for the resource allocation and monitoring, correlated with the process of software product innovation and evolution.

The analysis reveals that the specialized literature has moved beyond the introductory phase of defining sustainability and is increasingly focusing on operationalizing the concept within financial processes. The impact of this finding on our article is significant, as it confirms the opportunity to develop an operational model for cost estimation and revenue recognition that translates sustainability principles into accounting and decision-making tools applicable in software project practice. Thus, the figure highlights not only the prevalence of theoretical themes but also the clear direction to the consolidation of the field, oriented towards pragmatic solutions with an impact on financial reporting.

Simultaneously, the concentration of citations reveals a canonical core focused on planning and control, enhanced by recent contributions that connect the financial dimension with social and environmental responsibility, as well as with digital transformation (see Table 1). Therefore, the theoretical foundation and recent developments legitimize the integrative direction we propose, facilitating the transition from general principles to applicable procedures in IT companies.

Table 1. Top 10 articles and reference works on the research topic

Work (full title)	Author(s)	Year	Citations*	Type (article / book)
Project management: a systems approach to planning, scheduling, and controlling	Kerzner, H.	2025	14.892	John Wiley and Sons (14th edition)
Project management for engineering, business and technology	Nicholas, J. M. & Steyn, H.	2020	552	Routledge (Taylor & Francis)
Sustaining enterprise operations and productivity during COVID-19 "Enterprise Effectiveness and Sustainability Model"	Obrenovic, B. et al.	2020	523	*Sustainability* (MDPI)
Healthcare digitalization and pay-for-performance	Moro Visconti, R. & Morea, D.	2020	201	*International Journal of Environmental Research and Public Health* (MDPI)
Modeling factors of biogas technology adoption	Ali, S. et al.	2023	196	*Environmental Science and Pollution Research* (Springer)
Cost and value management in projects	Venkataraman, R. R. & Pinto J. K.	2023	192	John Wiley & Sons (2nd edition, revised)
A sustainable university: Digital transformation and cost allocation	Mohamed, M. A. et al.	2022	182	*Education and Information Technologies* (Springer)
Designing a robust cost allocation framework for sustainable projects	Chukwuma-Eke, E. C. et al.	2021	175	*International Journal of Multidisciplinary Research and Growth Evaluation* (IJMRGE)
A conceptual framework for financial optimization in project sustainability	Chukwuma-Eke, E. C. et al.	2022	146	*International Journal of Multidisciplinary Research and Growth Evaluation* (IJMRGE)
Business models for sustainable commercialization	Oderanti, F. O. et al.	2021	101	*Technological Forecasting and Social Change* (Elsevier)

** Number of citations as of September 2025*

Source: authors' own elaboration

Table 1 summarizes the top ten highly cited works in the international literature on sustainable budgeting and software project management, ranked by number of citations. It is observed that the core reference base is dominated by fundamental works in project management, such as the volumes by Kerzner (2025) and Nicholas

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and Steyn (2020) which together account for thousands of citations and confirm their status as methodological benchmarks for planning, control, and strategic coordination. These contributions constitute the foundation upon which subsequent applied research is built.

Also, there is an upward trend in publications focused on integrating sustainability, especially in internationally visible, open-access journals such as Sustainability and the International Journal of Environmental Research and Public Health. The articles by Obrenovic et al. (2020) and Moro Visconti and Morea (2020) demonstrate the increasingly strong connection between productivity, digitalization, and ESG criteria, confirming the shift in research focus from traditional management tools to models with social and ecological impact.

At the same time, recent works from Springer and Elsevier, such as Ali et al. (2023) and Oderanti et al. (2021), illustrate the focus on technology adoption models and sustainable commercialization, with cross-sector applicability. Likewise, the contributions of Chukwuma-Eke (2021, 2022) propose conceptual frameworks and operational methodologies for cost allocation and financial optimization, accumulating a significant number of citations in a relatively short period, a fact which confirms the academic community's interest in applied solutions.

The citation structure indicates two major directions: on the one hand, the consolidation of the theoretical foundation of project management through established reference works, and on the other hand, the emergence of a body of literature oriented towards sustainability, financial optimization, and digital integration. This dual orientation legitimizes the need to develop an operational model that combines cost estimation and revenue recognition with sustainability objectives, contributing to both the theoretical advancement and the practical relevance of the proposed research.

Overall, Table 1 reveals a dual structure of the impactful literature: on one side, project management works (Kerzner, 2025); Nicholas & Steyn, 2020) that provide the methodological framework for planning and control, and on the other, recent contributions oriented towards sustainability and digitalization, published mainly in high-visibility journals, which accelerates the visibility of results. The concentration of citations around studies that combine the financial dimension with ESG criteria suggests a shift in interest from general principles to operational tools. This configuration legitimizes the direction of our research: an operational model that connects cost estimation and revenue recognition within an explicit sustainability framework.

The analysis of the specialized literature confirms that the application of IFRS 15 is not a simple accounting exercise, but a process with structural effects on the way economic activities are conducted and on the relevance of financial reporting. The study published by Napier and Stadler (2020) demonstrates that, although the immediate accounting impact of the standard was relatively limited in European industries, the changes in contract structures and managerial decisions were significant, confirming the operational dimension of IFRS 15. Furthermore, the research by Onie et al. (2023) on a sample of Australian firms shows that, for some companies, the transition had substantial effects on earnings and equity, suggesting that the relevance of financial information depends on the quality of internal progress measurement mechanisms and the rigorous allocation of the transaction price.

Against this backdrop, the research of Grosu et. al. (2022) offers a perspective adapted to emerging economies, highlighting that the implementation of IFRS 15 requires innovative methodological solutions and institutional adaptations, especially where resources are limited. This contextual dimension confirms the need for flexible operational models applicable across different economic realities, including in the Republic of Moldova and Romania, where the IT sector plays a strategic role.

Furthermore, the study by Cojocaru, Șoimu, and Bădicu (2025) demonstrates that in the software industry, contract complexity requires advanced technological solutions, and the use of artificial intelligence can increase the accuracy and consistency of IFRS 15 application. However, the authors emphasize that the professional judgment of the accountant remains indispensable, indicating the need for clear, coherent, and reliable conceptual models capable of supporting managerial decisions-making. At the same time, the analysis by Bădicu, Cojocaru, and Nancu (2023) shows that cost estimation for custom software development is impossible

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without a detailed assessment of the design, objectives, and resources involved, and in practice, personnel expenses represent the greatest accounting challenge.

As a whole, these contributions confirm two essential directions. On one hand, IFRS 15 drives a reconfiguration of contracting and revenue recognition processes, and the success of its implementation depends on the quality of the methodologies and tools used, including AI-based ones. On the other hand, the lack of clear approaches to software cost estimation highlights the need for an integrated operational model. Our research addresses this dual challenge by proposing a framework that combines revenue recognition according to IFRS 15 with sustainable cost estimation, adding the dimension of financial responsibility and sustainability to software project management.

3. Research Methodology

3.1. Research Design

This study employs a multi-method research design consisting of three complementary components:
(i) bibliometric analysis, used to map existing knowledge and establish the research hypotheses;
(ii) development of an integrated operational model, based on a design-science approach;
(iii) validation through a single-case study, applied to a real software contract.

This structure ensures clear separation between methods, data, and results, in line with the standards of Entrepreneurship and Sustainability Issues.

3.2. Method A: Bibliometric Analysis

The bibliometric search was conducted using Publish or Perish v8, querying Scopus and Google Scholar. The search combined controlled terms and free-text expressions: "sustainable budgeting" and "software"; "software project" and ("cost estimation" or "project budgeting"); "IFRS 15" and "revenue recognition" and "software"; "sustainability" and "financial performance".

Time window (2020–2025): selected to capture the mature application of IFRS 15 and the rise of sustainability-focused budgeting in digital industries.

Inclusion criteria:

- peer-reviewed journal articles or scholarly books;
- direct relevance to sustainable budgeting, software cost estimation, IFRS 15/IAS 38, or performance indicators such as CPI/SPI;
- published in English;
- publication period 2020–2025.

Exclusion criteria:

- editorials, opinion pieces, commentaries, or preprints without peer review;
- technical engineering papers without financial or accounting relevance;
- duplicates or records with insufficient scientific quality.

The screening and selection process was carried out in three stages:

1. Title-abstract screening, used to eliminate studies that were clearly unrelated to sustainable budgeting, software project management, or IFRS-based financial reporting.
2. Full-text eligibility assessment, during which the remaining studies were evaluated against the predefined inclusion and exclusion criteria.
3. Deduplication and final validation, ensuring the removal of repeated records and the retention of high-quality, relevant sources.

Following this procedure, a total of 100 studies were included in the final bibliometric dataset, forming the basis for the development of research hypotheses H1–H3.

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For each study we extracted: outlet, year, method, industry context, IFRS treatment, sustainability integration, cost-estimation approach, and indicators (CPI/SPI). Term-frequency mapping confirmed the centrality of themes relevant to this study.

To strengthen the link between the bibliometric findings and the formulation of the research hypotheses, an evidence matrix was constructed. Table 2 synthesizes representative studies, the thematic justification for each hypothesis, and the relevant keywords extracted during the bibliometric screening process.

Table 2. Evidence matrix for the research hypotheses

Research hypotheses	Short description of the analyzed hypothesis	Bibliographic references	Relevant keywords supporting the association with the hypothesis
H1	Sustainable budgeting in software projects increases financial transparency and reduces the risk of budget instability.	Okeke, Bakare & Achumie (2024); Andreotti et al., (2024); Adepoju, et al. (2023); Waheeb & Kocins (2023); Chukwuma-Eke, Ogunsola & Isibor (2021).	Financial Stability; Budgeting and Revenue; Business objectives, Risk management; Sustainable Development; Risk Management; Performance Evaluation
H2	Integrating costs and recognizing revenues progressively ensures a closer alignment with international reporting standards, especially IFRS 15.	Remeňová, Kintler & Jankelová, (2020); Okeke, Bakare & Achumie, 2024; Orieno et al. (2024); Maritan et al. (2024).	Revenue; Recognition; IFRS 15; Sustainability
H3	The integration of sustainable budgeting into software development enhances competitiveness and ensures long-term organizational resilience.	Orieno et al. (2024); Atz et al. (2020); Zarjou & Khalilzadeh (2022); La Torre et al. (2024).	Sustainability Concepts; Efficiency; Performance

** Relevant keywords were extracted from the titles and abstracts based on the bibliometric analysis.*

Source: authors' own elaboration

3.3. Method B: Development of the Integrated Operational Model

Design-science approach

The model was created using a structured design-science procedure:

- problem identification;
- formulation of design requirements;
- iterative construction of the dual-flow model;
- definition of internal validation criteria.

Dual-flow model architecture

1) Operational flow

Captures project progress and resource consumption:

- backlog, sprints, milestones;
- timesheets and effort allocation;
- cost estimation using Job Costing, ABC, TD-ABC;
- progress measurement through input-based (cost-to-complete) and output-based deliverables.

2) Financial–accounting flow

Translates operational progress into IFRS-compliant financial outputs:

- performance obligation identification;
- transaction-price allocation;
- progress-based revenue recognition;
- variable consideration (royalties);
- IAS 38 capitalization criteria.

Vertical alignment ensures full cost–revenue traceability.

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Key operational definitions
Let EVt denote the earned value (proxied by IFRS 15 revenue) and AC_t the actual cost.

$$(1)\ CPt = \frac{EVt}{ACt}$$

$$(2)\ MAPE = \frac{1}{N}\sum\left|\frac{Actual-Forecast}{Actual}\right|$$

$$(3)\ Gross\ Margin = [\frac{Revenue-Cogs}{Revenue}]\times 100$$

These equations operationalize the core efficiency, accuracy, and profitability measures used to validate the integrated model. CPI reflects execution discipline, MAPE quantifies forecasting accuracy, and Gross Margin expresses financial resilience.

Internal validation criteria
- logical consistency between flows;
- alignment with IFRS 15;
- auditability and reproducibility of calculations;
- transparency of assumptions.

3.4. Method C: Case Study and Model Validation

Case context
Validation was conducted through a two-year commercial software contract including:
1. license + customization (single performance obligation);
2. maintenance (periodic recognition);
3. royalties (usage-based variable consideration).

Cost categories: personnel, IT infrastructure, indirect costs, technical maintenance.

Variables and indicators
- H1 (transparency and risk): cost–budget variance, MAPE/MAE, CPI/SPI.
- H2 (IFRS alignment): IFRS 15 compliance score, managerial vs IFRS revenue, restatement incidence.
- H3 (performance and resilience): gross margin, operating profit, cash-flow stability, on-time delivery; sensitivity (±10–20% users).

Analysis procedure
1. Compile quarterly cost–revenue datasets;
2. Compute CPI, MAPE, Gross Margin;
3. Run sensitivity analysis;
4. Apply concordance tests;
5. Consolidate findings in a validation scorecard.

Validity and reliability
- construct validity via IFRS-consistent progress measures;
- internal validity via triangulation;
- external validity via transparent parameters;
- reliability via reproducible calculation templates.

3.5. Data

Bibliometric data: 100 peer-reviewed sources (2020–2025) retrieved from Scopus and Google Scholar.
Model development data: Backlog documents, milestones, timesheets, cost data, accounting policies (IFRS 15/IAS 38).
Case study data: Contract terms, pricing components, user volumes, quarterly revenues, cost categories.

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4. Results and Discussions

4.1. Results of the Bibliometric Analysis

The bibliometric analysis generated several empirical insights that support the motivation and structure of the study. As presented in Figure 1 (keyword frequency distribution) and Table 1 (top-cited works), the 2020-2025 literature exhibits a distinct convergence between software project management, sustainability-oriented practices, and accounting frameworks such as IFRS 15.

The high frequency of terms such as "sustainable", "project(s) ", "software", "management", and "budgeting" indicates a shift in the field from conceptual sustainability narratives toward operational and methodological integration. The presence of IFRS-related keywords confirms that financial reporting and revenue-recognition mechanisms increasingly interact with budgeting and performance evaluation in the software sector.

Table 1 strengthens this conclusion by showing that the most influential works sit at the intersection of cost estimation, transparency, performance measurement, and governance. However, despite these overlaps, no study offers an operational model that unifies cost estimation, progress-based revenue recognition, and sustainability-driven budgeting.

These bibliometric results validate the theoretical gap addressed in the present paper and justify the development of an integrated dual-flow model that aligns managerial, accounting, and sustainability dimensions.

4.2. Results of the Integrated Operational Model

Figure 2 presents the integrated operational model developed in this study, structured around two mutually reinforcing flows: the operational flow, which captures measurable project progress and resource consumption, and the financial–accounting flow, which converts this progress into revenue recognized under IFRS 15. The model operationalizes the alignment between cost estimation, progress measurement, and revenue recognition through a system of vertical checkpoints that synchronize technical milestones with financial reporting.

The results show that the dual-flow architecture ensures full traceability between resources consumed, value delivered, and revenue recognized. On the operational side, the model produces consistent, auditable progress measurements based on timesheets, backlog evolution, and milestone acceptance. On the financial-accounting side, the model translates these operational measures into structured outputs: identification of performance obligations, allocation of the transaction price, progress-based recognition for license and customization components, periodic recognition for maintenance, and variable consideration for royalties.

The integration points between the two flows demonstrate that managerial cost estimation and IFRS 15 mechanisms can operate within a single system without internal inconsistencies. The checkpoints eliminate timing mismatches between operational progress and revenue recognition, allowing budgeting, forecasting, and financial reporting to follow the same logic of value delivery. This result supports the central premise of the study: that a unified, sustainability-oriented budgeting framework becomes feasible only when operational and accounting processes are technically synchronized rather than running in parallel.

Moreover, the model produces structured outputs that can be directly incorporated into budget updates, performance dashboards, and internal-control routines. These outputs include quarterly earned-value estimates, IFRS 15-compliant revenue schedules, and cost-to-complete profiles that can be used by both project managers and financial controllers. As such, the application of Figure 2 in the case study (Sections 4) demonstrates that the model functions not only conceptually but also as a practical tool that can improve transparency, alignment, and execution discipline.

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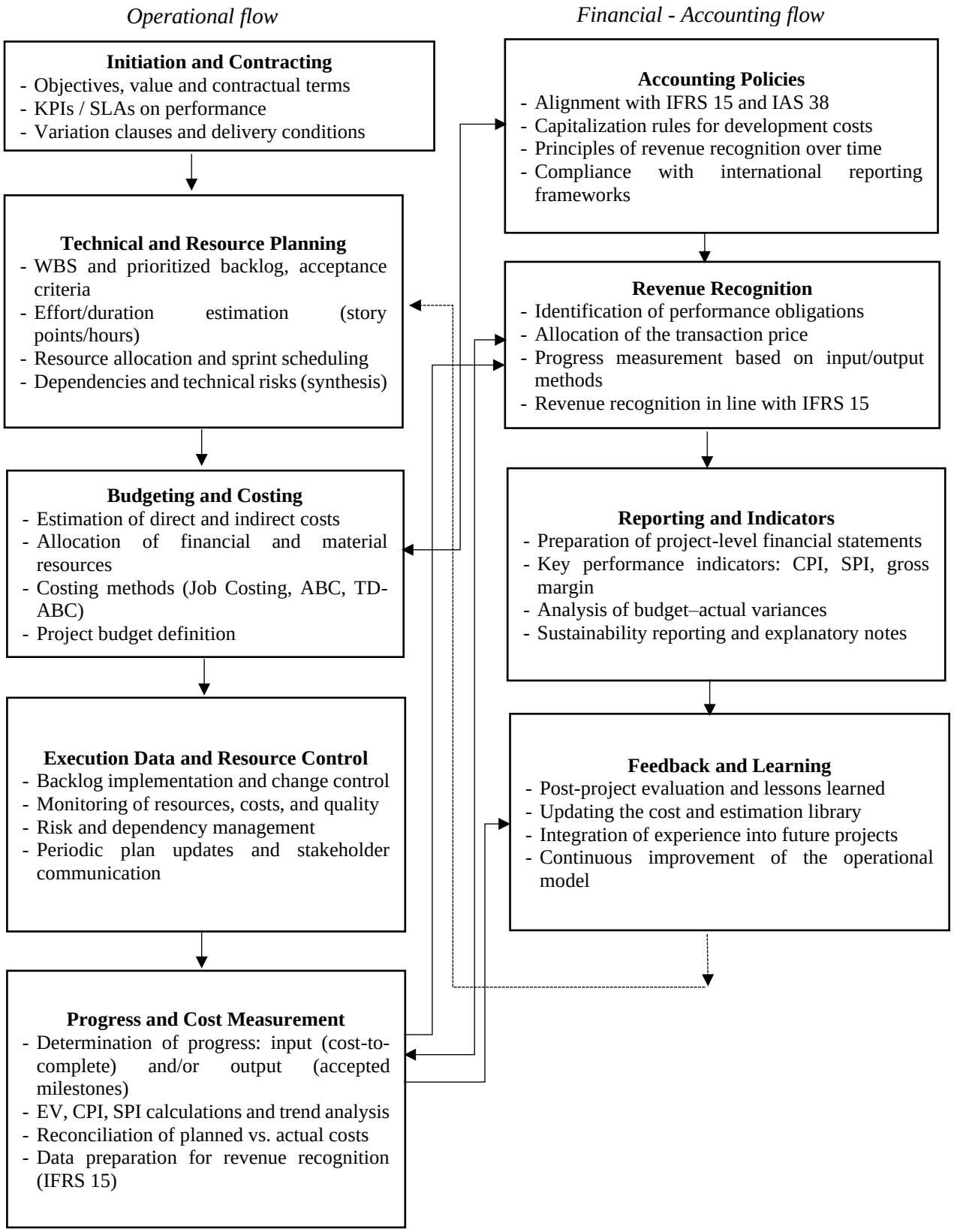


Figure 2. Integrated operational model for sustainable budgeting and revenue recognition in software projects
Source: authors' own elaboration

Figure note. The operational flow supplies inputs for cost estimation and progress measurement (timesheets, backlog, milestones), while the financial–accounting flow maps these measures to IFRS 15 revenue recognition and IAS 38 cost treatment; vertical checkpoints synchronize the flows, ensuring traceability between resources, delivered value, and recognized revenue within a sustainability-oriented budgeting routine.

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4.3. Case Study Results

Table A1 reports the quarterly revenue recognized under IFRS 15 across the eight-quarter duration of the software contract. Total revenue amounts to EUR 1,057,500, with the largest share generated by license and customization activities, followed by maintenance services and usage-based royalties. Detailed quarterly revenue data are provided in Appendix A (Table A1). Revenue levels remain relatively stable across the first six quarters, with moderate variability driven by changes in user adoption. The royalty component grows gradually over time, reflecting increased system usage and the contractual design of variable consideration. This pattern confirms that revenue recognition under IFRS 15 is closely tied to value delivered through accepted milestones and verified usage.

4.4. Cost Results

Table A2 presents the associated cost structure by quarter. Personnel costs represent the dominant share of expenses throughout the project, consistent with the labor-intensive nature of software development. IT infrastructure costs are concentrated in the initial two quarters, during the setup and architecture phase, while indirect and maintenance-related costs remain relatively stable throughout the contract. Detailed quarterly cost data are provided in Appendix A (Table A2)

The quarterly distribution illustrates a front-loaded cost pattern followed by stabilization, which aligns with the operational flow from Figure 2. This cost behavior helps explain the progressive improvement in margins observed across the project timeline.

4.5. Performance Indicators

Table 3 summarizes the key performance indicators. The Cost Performance Index (CPI) remains consistently above 1.00 for all eight quarters, increasing from approximately 1.24 in the early stages to 1.76 in the later periods. This upward trajectory indicates efficient resource utilization and reduced cost variance as the project matures.

Table 3. Overview of revenues, costs, and performance indicators of the software project

Year/ Quarter	Total Revenue	Total Cost	Gross Profit	Cost Performance Index (CPI)	Revenue variation (%)	Gross Margin, %
Y1-Q1	126.000	101.875	24.125	1.24	0.8	19.15
Y1-Q2	127.500	101.875	25.625	1.25	2.0	20.10
Y1-Q3	129.000	79.375	49.625	1.63	3.2	38.46
Y1-Q4	130.000	79.375	50.625	1.64	4.0	38.94
Y1 Total	**512.500**	**362.500**	**150.000**	**1.41**	**2,5**	**29.27**
Y2-Q1	132.500	79.375	53.125	1.67	6.0	40.09
Y2-Q2	135.000	79.375	55.625	1.70	8.0	41.20
Y2-Q3	137.500	79.375	58.125	1.73	10.0	42.27
Y2-Q4	140.000	79.375	60.625	1.76	12.0	43.30
Y2 Total	**545.000**	**317.500**	**227.500**	**1.71**	**9.0**	**41.74**
Y1 and Y2 Total	**1.057.500**	**680.000**	**377.500**	**1.56**	**5.75**	**35.70**

Source: authors' own elaboration

Performance metrics (Equations 1–3) were applied to quarterly data to assess execution efficiency and forecasting accuracy.

Gross margin improves significantly - from approximately 19% in the initial quarters to approximately 43% toward the end of the project. This increase is supported by stabilizing costs and increased royalty revenues, demonstrating the reinforcing effect of both operational efficiencies and usage-driven receipts.

Forecast accuracy indicators (MAPE/MAE), where applicable, confirm a decreasing variance between planned and realized values over time. These results validate the relevance of the integrated model: the combination of

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operational progress measures and IFRS 15 recognition improves cost–revenue alignment, execution discipline, and financial resilience.

4.6. Sensitivity analysis

Table 4 reports the results of the sensitivity analysis conducted on the variable consideration component (royalties), based on simulated changes in the number of active users (±10% and ±20%). Because royalties are calculated exclusively on usage above the 1.fas000-user threshold, the impact on financial performance is proportional and affects only one revenue component, while the fixed-price elements remain unchanged.

Table 4. Sensitivity analysis of royalties and gross margin

Scenario	Royalties (EUR)	Total Revenue (EUR)	Total Cost (EUR)	Gross Margin (%)
–20% users	46.000	1.046.000	680.000	34.97%
–10% users	51.750	1.051.750	680.000	35.34%
Baseline	57.500	1.057.500	680.000	35.69%
+10% users	63.250	1.063.250	680.000	36.05%
+20% users	69.000	1.069.000	680.000	36.40%

Source: authors' own elaboration

A decrease of 20% in active users reduces royalties from EUR 57.500 to EUR 46.000 and total revenue to EUR 1.046.000. The gross margin declines moderately from 35.69% (baseline) to 34.97%. Conversely, a 20% increase in users raises royalties to EUR 69.000, total revenue to EUR 1.069.000, and gross margin to 36.40%.

The narrow variation interval (approximately ±0.7 percentage points around the baseline margin) demonstrates that the project remains financially resilient even under unfavorable adoption scenarios. These results validate H3 by confirming that the integrated operational–financial model maintains stability under variable-usage conditions, ensuring transparency and predictable performance for sustainability-oriented budgeting in digital environments.

4.7. Hypotheses Validation

We triangulate Tables 3–4 and Appendix Tables A1–A2, together with the KPI formulas (Equations 1–3), to test H1–H3 using the operationalization and validation grid defined in the research design.

H1 – Transparency and risk reduction.

Across all eight quarters, the Cost Performance Index (CPI) remains at or above 1.24 and increases to 1.76 in the final period, while gross margin improves from approximately 19% to around 43% and revenue variance decreases over time. Taken together, these patterns indicate that execution discipline strengthened and budget risk declined as the project stabilized, supported by the consistent mapping of operational progress measures to IFRS 15 recognition schedules. Therefore, H1 is accepted, with CPI, MAPE/MAE and revenue variance serving as the key supporting indicators.

H2 – Alignment with IFRS 15.

The revenue patterns reported in Table 4 and Appendix Table A1 show that each component of the contract is recognized in a manner consistent with its underlying performance obligations: license and customization are recognized uniformly over the project horizon, maintenance is recognized periodically, and royalties are recognized as usage-based variable consideration. The quarterly schedules remain internally consistent and mirror the operational milestones defined in the integrated model, with no timing mismatches between value delivery and revenue recognition. This concordance between managerial progress measures and IFRS 15 revenue profiles indicates that the dual-flow framework effectively embeds the standard's principles into budgeting and reporting routines. Therefore, H2 is accepted, with IFRS 15 compliance, the alignment between managerial and IFRS revenues, and the absence of recognition restatements acting as the main supporting indicators.

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H3 – Performance and resilience.
The profitability patterns presented in Table 3 and the sensitivity results in Table 4 indicate that the project maintains a stable financial profile across all quarters. Gross margin increases from approximately 19% in the early stages to about 43% by the end of the contract, driven by cost stabilization and growing royalty revenues. Sensitivity scenarios of ±10–20% active users produce only minor fluctuations in profitability, with gross margin remaining within a narrow interval of roughly ±0.7 percentage points around the baseline. This stability under varying demand conditions reflects the robustness of the integrated operational–financial model and its capacity to absorb fluctuations in variable consideration without compromising execution quality or financial outcomes. Therefore, H3 is accepted, supported by the sustained improvement in gross margin, the positive profitability trend, and the resilience demonstrated in the sensitivity analysis.

5. Conclusions

This study addressed the need for an operationally grounded and IFRS-consistent framework capable of supporting sustainability-oriented budgeting in software projects. By integrating cost estimation, progress measurement and revenue recognition into a single dual-flow model, the research offers a structured response to the long-standing fragmentation between managerial accounting routines and financial reporting requirements in digitally intensive environments.

The empirical results derived from the two-year commercial contract confirm that the proposed model improves transparency, enhances execution discipline and reduces budget risk, as demonstrated by consistently positive CPI values and the narrowing of revenue variance over time. The financial–accounting flow, grounded in IFRS 15, remained fully aligned with operational progress, ensuring coherent, milestone-based revenue recognition and eliminating timing mismatches. Profitability indicators strengthened progressively, and sensitivity scenarios showed that gross margin remained stable even under ±10–20% fluctuations in active-user volumes, demonstrating the resilience of the model under variable-demand conditions.

From a managerial perspective, the model provides a practical mechanism for linking budgeting, forecasting and reporting processes, enabling organizations to monitor resource consumption, value delivery and profitability within a unified system. For policy and regulatory contexts, the findings underline the importance of disclosure practices that reconcile managerial KPIs with IFRS-based revenue profiles, supporting auditability, transparency and sustainability-driven governance in technology-intensive firms.

Future research may extend this framework to multi-project environments, agile portfolio management settings or other digital industries where variable consideration and milestone-based delivery are prevalent. Further studies may also evaluate the integration of non-financial sustainability indicators or ESG-related performance metrics, allowing for an expanded understanding of sustainable budgeting in complex technological ecosystems.

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Appendix A. Supporting Data

Table A1. Quarterly revenue breakdown (Y1–Y2)

Year/ Quarter	Active Users	License Revenue (uniform)	Maintenance Revenue	Royalties Revenue (5 EUR × active users > 1.000)	Total Revenue
Y1-Q1	1.200	112.500	12.500	1.000	126.000
Y1-Q2	1.500	112.500	12.500	2.500	127.500
Y1-Q3	1.800	112.500	12.500	4.000	129.000
Y1-Q4	2.000	112.500	12.500	5.000	130.000
Y1 Total	**6.500**	**450.000**	**50.000**	**12.500**	**512.500**
Y2-Q1	2.500	112.500	12.500	7.500	132.500
Y2-Q2	3.000	112.500	12.500	10.000	135.000
Y2-Q3	3.500	112.500	12.500	12.500	137.500
Y2-Q4	4.000	112.500	12.500	15.000	140.000
Y2 Total	**13.000**	**450.000**	**50.000**	**45.000**	**545.000**
Y1 and Y2 Total	**19.500**	**900.000**	**100.000**	**57.500**	**1.057.500**

Source: authors' own elaboration

Table A2. Quarterly cost breakdown (Y1–Y2)

Year/ Quarter	Total Revenue	Personnel expenses	IT infrastructure costs	Indirect costs	Technical maintenance costs	Total Cost
Y1-Q1	126.000	67.500	22.500	5.625	6.250	101.875
Y1-Q2	127.500	67.500	22.500	5.625	6.250	101.875
Y1-Q3	129.000	67.500	0	5.625	6.250	79.375
Y1-Q4	130.000	67.500	0	5.625	6.250	79.375
Y1 Total	**512.500**	**270.000**	**45.000**	**22.500**	**25.000**	**362.500**
Y2-Q1	132.500	67.500	0	5.625	6.250	79.375
Y2-Q2	135.000	67.500	0	5.625	6.250	79.375
Y2-Q3	137.500	67.500	0	5.625	6.250	79.375
Y2-Q4	140.000	67.500	0	5.625	6.250	79.375
Y2 Total	**545.000**	**270.000**	**0**	**22.500**	**25.000**	**317.500**
Y1 and Y2 Total	**1.057.500**	**540 000**	**45.000**	**45.000**	**50.000**	**680.000**

Source: authors' own elaboration

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DEMOGRAPHIC DETERMINANTS OF ENTREPRENEURIAL INTENTION IN A TRANSITION ECONOMY: EVIDENCE FROM THE CZECH REPUBLIC*

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Abstract. This scientific paper examines the demographic factors influencing Entrepreneurial Intention (EI) in the Czech Republic, a Central and Eastern European (CEE) transition economy. Understanding who is most inclined toward Start to Business activities is crucial for tailoring effective policy interventions aimed at New Venture Creation and sustained economic growth. The primary scientific goal was to empirically examine the potential connections between the general characteristics of the respondent and their influence on the intention to start a business, thereby identifying the demographic segments most responsive to policy interventions (Age, Gender, Highest Educational Attainment, and Economic Educational Focus). Using the Chi-Squared Test of Independence and Logistic Regression, the empirical analysis revealed a highly significant negative correlation between Age and EI ($p<.001$), confirming the established life-cycle theory: the intention to start a business decline by 1.489% for every one-year increase in age. Conversely, no statistically significant influence was found for Gender ($p=0.567$), general education level ($p=0.108$), or specialized Economic Educational Focus ($p=0.372$). This major anomaly (the failure of formal education to boost EI) suggests structural inefficiencies within the Czech entrepreneurship education system, implying that educational institutions are not successfully transferring the practical skills required to increase Perceived Behavioral Control. This suggests the ecosystem's significant reliance on latent factors, such as the high prevalence of a family entrepreneurial background (58.12%), which likely serves as a crucial compensatory mechanism for weak institutional inputs. Policy recommendations advocate for age-segmented support and a systemic overhaul of economic education curricula.

Keywords: Small and medium-sized enterprises; Entrepreneurial Intention; Business Environment

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JEL Classifications: M21, M50, O44

Additional disciplines: political sciences; sociology; psychology

1. Introduction

Entrepreneurship is generally considered to be the driving force of a market economy. In order to develop entrepreneurship, it is important to create suitable conditions for the business sector. At the same time, it is necessary to create opportunities for motivation and easy entry of citizens into entrepreneurship, both by

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removing administrative or technical barriers, as well as by tools supporting people to accept entrepreneurship as a way of their application in the labor market. The culture of building entrepreneurs and entrepreneurially oriented people is particularly important in the conditions of the countries of Central and Eastern Europe, whose economies are still considered to be in transit and where the possibility of free enterprise has been limited for more than 40 years.

Entrepreneurship is today widely recognized as a critical force in economic evolution, serving as a primary source of organizational survival, technological innovation, and sustained economic growth, particularly in the modern knowledge economy (Shi & Wang, 2021). The classic Schumpeterian perspective views the entrepreneur as the 'prophet of innovation,' inextricably linking their creative actions to the core of economic development (Binnui & Cowling, 2016). This role is not merely self-serving but is crucial for injecting new vitality into the national economy, constantly creating and refreshing industrial structures (Wang, Wang & Chen, 2018).

The fundamental goal of this process is new venture creation (or start to business), which is neither accidental nor spontaneous; it requires deliberate planning and intentionality on the part of the individual. Because of the inherent difficulty and high uncertainty associated with launching a new firm, understanding the psychological and demographic antecedents of this effort is vital (Ranga et. al., 2019; Mefi & Asoba, 2025).

2. Theoretical Background of Entrepreneurial Intention and Entrepreneurial Ecosystem

Entrepreneurial intentions are often defined differently by researchers. Entrepreneurial Intention (EI) is defined as the amount of effort an individual is willing to exert to behave in a specific manner, and it is confirmed in the literature as the strongest predictor of eventual entrepreneurial behavior (Martínez-González et al., 2019).

The analysis of EI relies heavily on two complementary cognitive models: Ajzen's (1991) Theory of Planned Behavior (TPB) and Shapero and Sokol's Model of the Entrepreneurial Event (SEE), summarize Ranga et al. (2019).
The Theory of Planned Behavior (TPB) posits that intention is a function of three key determinants:

1. **Attitude Towards Behavior (AAB):** The individual's evaluation of the behavior, reflecting whether they perceive starting a business as favorable, valuable, and beneficial (Rakib, et al. 2020). Key motivations include the desire for self-achievement, individual goals, social recognition, and a proactive competition/market focus (Wu & Mao, 2020).
2. **Subjective Norms (SN):** The perceived social pressure or support from key reference groups (e.g., family, peers) regarding the desirability of entrepreneurship (Adam et al., 2021).
3. **Perceived Behavioral Control (PBC):** The individual's self-assessment of their capacity and ability to perform the behavior successfully, often referred to as entrepreneurial self-efficacy (Rakib et al., 2020).

The Model of the Entrepreneurial Event (SEE) similarly emphasizes perceived desirability and perceived feasibility as central drivers of entrepreneurial intent (Iakovleva & Kolvereid, 2009). Intentions are typically initiated by subjective variables (beliefs, social norms, values) which then influence action variables (motivation, self-efficacy, and ultimately, intention), written by Martínez-González et al. (2019). Entrepreneurial intention is shaped not only by individual cognitive factors but also by the surrounding Entrepreneurial Ecosystem, encompassing both institutional support and cultural norms (Aguilar Cruz, 2022).

Based on the available research, we can claim that the business environment, or the overall Entrepreneurial Ecosystem consists of the following three key areas:

- Institutional Support: Government policies, as well as the quality of education and training programs, play a pivotal role by influencing entrepreneurial attitudes and providing access to critical resources (Liu & Yao-Ping Peng, 2025). The quality of education and training is specifically hypothesized to affect entrepreneurial motivation positively (Hudáková et al., 2020; Vandor, 2021).
- Education and Training: Formal education is expected to enhance EI by building human capital and increasing PBC (Perceived Behavioral Control). However, studies consistently show that if Entrepreneurship Education is "imperfect" or overly theoretical, it may fail to reduce the perceived fear

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of failure or increase risk-taking, rendering its impact on entrepreneurial intention minor or even negative (Liu et al., 2022; Deng & Wang, 2023; Manchidi, 2025).

- Cultural Context: Cultural values, such as 'Hierarchy' and 'Mastery', have been empirically shown to increase Entrepreneurial Intention (Xanthopoulou et al., 2025).

General characteristics like age, gender, and education are considered exogenous variables that indirectly modulate these core cognitive constructs of The Theory of Planned Behavior (AAB, SN, PBC). Identifying the demographic profiles most receptive to external intervention is essential for designing effective policies (Wassink, 2020).

3. Research Objectives and Methodology

The Czech Republic provides a unique institutional and socio-economic environment for Entrepreneurial Intention analyzing. As a Central and Eastern European (CEE) economy, its history involves a transition from a planned system, meaning its current ecosystem is shaped by a need to cultivate opportunity-driven, high-tech entrepreneurship. The study specifically addresses the lack of large-sample analyses on fundamental demographic predictors within this CEE context.

The overall scientific objective (goal) of this research article is to empirically examine the potential connections between the general characteristics of the respondent and their influence on the intention to start a business, thereby identifying the demographic segments most responsive to policy interventions.

When elaborating this scientific paper, we used theoretical knowledge and information obtained from available domestic as well as foreign literary sources consisting primarily of secondary information sources. The secondary sources of information were data and knowledge obtained through the study, processing and analysis of scientific and professional publications, as well as available other comparative researches, where we monitor selected indicators of business environment and entrepreneurship intend.

The primary information, which was used when writing the paper, was represented by the questionnaire-based survey conducted throughout the Czech Republic in an effort to scientifically identify the current state of perception of attitudes to business environment and entrepreneurship intend (entry motives and issues), while focusing also on the area of identification of key demographic determinants. Data collection from the implemented questionnaire was carried out through quota sampling, with the quota set for equal geographical representation by region. The distribution itself was carried out electronically and through random sampling. Respondents were addressed in the second half of 2024. The empirical analysis utilized a sample of N=1096 non-entrepreneurial respondents from the Czech Republic (derived from a total sample of N=1284 individuals). The dependent variable, Intention to start a business, was treated as a dichotomous (binary) variable.

The study was structured around one overall scientific objective and four specific research questions (RQ1-RQ4) designed to test the influence of general respondent characteristics on the intention to start a business (see Table 1).

Table 1. Research Questions and Hypotheses

Research Question (RQ)	Null Hypothesis (H0)	Alternative Hypothesis (H1)
RQ 1: Does a connection exist between an individual's highest attained education and the consideration of starting a business?	An individual's highest attained education does not influence their intention to start an entrepreneurial activity.	An individual's highest attained education influences their intention to start an entrepreneurial activity.
RQ 2: Does a connection exist between gender and the consideration of starting a business – do men or women have greater intentions to start a business?	An individual's gender does not influence their intention to start an entrepreneurial activity.	An individual's gender influences their intention to start an entrepreneurial activity.

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RQ 3: Do graduates of economic education more frequently consider the idea of starting a business?	The nature of an individual's education does not influence their intention to start an entrepreneurial activity.	The nature of an individual's education influences their intention to start an entrepreneurial activity.
RQ 4: Does a connection exist between age and the consideration of starting a business – do younger age groups more frequently consider the idea of starting a business?	An individual's age does not influence their intention to start an entrepreneurial activity.	An individual's age influences their intention to start an entrepreneurial activity.

Source: own research

To test the hypotheses concerning gender and educational attainment/focus (RQ 1 – RQ 3) – which involve a qualitative nominal dependent variable and qualitative nominal independent variables – the Chi-Squared Test of Independence was employed. This statistical test assesses whether a relationship exists between the two categorical variables.

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{C} \frac{(O_{ij} - E_{ij})^2}{E_{ij}}$$

Where:
O_{ij} – Observed Frequency
E_{ij} – Expected Frequency

This statistic asymptotically approaches a χ^2 division with the r-1 degrees of freedom. It is based on the frequency table and tests the null statistical hypothesis stating that the numbers in the individual categories are equal to the expected (theoretical) numbers (Rimarčík, 2007).

To assess the influence of age (RQ 4) – where the independent variable is a quantitative ratio variable and the dependent variable is qualitative nominal – Logistic Regression was utilized. Logistic Regression is a statistical model used to predict the probability of a binary outcome (dichotomous outcome: 0 or 1, Yes or No).

$$\pi(X) = \frac{1}{1 + e^{-(\beta_0 + \sum_{i=1}^{k} \beta_i X_i)}}$$

Where:
β0 – Intercept (The predicted log-odds of the outcome when all predictor variables)
βi – Regression Coefficient (The coefficient estimated for the independent variable)
Xi – Independent Variable – Predictor (The i-th variable used to predict the outcome)
k – Number of Predictors (The total number of independent variables in the model).

This approach was selected to preserve the full informational value of the age variable and precisely quantify its impact on the probability of reporting entrepreneurial intention (Hosmer, Lemeshow & Sturdivant, 2013). In our case, logistic regression models the probability of intention to enter entrepreneurship based on age (see Table 2).

Table 2. Demographic Profile of Survey Respondents

Characteristic	Categories	Count (N)	Percentage (%)
Gender	Male	463	42.24%
	Female	633	57.76%
Education: Economic Focus	Yes	309	28.19%
	No	787	71.81%
Family Entrepreneurial Background (FEBB)	Yes	637	58.12%
	No	459	41.88%

Source: own research

The sample profile reveals key characteristics: 42.24% male and 57.76% female. Notably, 58.12% of respondents reported having a family entrepreneurial background (FEBB), and 28.19% reported having an economic-focused educational background.

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4. Results and Discussion

The first part of analysis was oriented on Analysis of Categorical Variables (Chi-Squared Tests) – RQ 1 – RQ 3 (Highest education, Gender and Economic background). The second part analyzed Quantitative Variable (Logistic Regression for Age).

Highest Educational Attainment (RQ 1) and Economic Background (RQ 3) - The Education Paradox: Structural Deficiency in Formal Training

According to Liu et al. (2022), formal education is fundamentally expected to enhance entrepreneurial intentions by providing knowledge (human capital) and increasing perceived capacity (PBC). Economic and business studies are particularly expected to boost EI, as they provide practical details that make entrepreneurship seem more attractive and feasible and often show a positive influence on attraction and capacity (Iakovleva & Kolvereid, 2009). Furthermore, technical or scientific education also often correlates positively with higher EI due to specialized skill sets and inherent risk appetite (Yan, Huang & Xiao, 2023). However, a meta-analytic review confirmed that the link between business education and entrepreneurial intentions is often inconsistent (Zisser et al., 2019).

Table 3. Chi-Squared Tests for Influence of education

	Value	df	p
X^2	10.41	6	.108
N	1.096		

Source: own research

The relationship between the highest completed education level (ranging from basic to PhD) and the intention to start a business was tested. The Chi-Squared Test yielded a value of 10.41 (df=6), with a resulting p-value of 0.108. Since $p > 0.05$, the influence of the highest attained education on entrepreneurial intention could not be statistically demonstrated (see Table 3).

A specific test was conducted to determine if graduates with an economic focus display a higher intent to enter entrepreneurship. The Chi-Squared Test resulted in a value of 0.796 (df=1) and a p-value of 0.372 (see Table 4). As with the other categorical variables, this result led to the conclusion that absolvents of economic education do not demonstrate a statistically significant greater intention for entrepreneurial activity.

Table 4. Chi-Squared Tests for Influence of Economic education

	Value	df	p
X^2	0.796	1	0.372
N	1.096		

Source: own research

The non-significant influence of education—particularly the failure of economic-focused studies to enhance EI (p-value = 0.372) – represents a major anomaly in the context of international literature, which often confirms a positive link between business education and increased capacity and attraction (Liu et al., 2022).

This contradiction supports the hypothesis that the Czech Republic's formal Entrepreneurship Education (EE) system suffers from structural inadequacies, aligning with studies that discuss the negligible impact of "imperfect EE" (Deng & Wang, 2023). The implication is that educational institutions, despite being a core pillar of the institutional environment, are effective only at conveying theoretical knowledge but fail to successfully transfer the necessary practical skills and foster the risk tolerance required to increase perceived behavioral control (PBC). The importance of education at every age, is also confirmed by Bursová et al. (2024). If formal training cannot differentiate entrepreneurial intent from the general population, it suggests that the

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educational mechanism is not functioning as an effective accelerator of human capital formation in this critical domain. This diagnosis is essential: policy resources aimed at education must address pedagogical content and quality, not just access.

Gender (RQ 2): Gender Parity: An Alignment with Modern Trends

To assess whether a gender difference in entrepreneurial intention exists, the Chi-Squared Test produced a value of 0.328 (df=1). The corresponding p-value was 0.567. Given that this value far exceeds the standard 0.05 threshold, the analysis confirms that gender does not have a statistically significant influence on the intention to start a business in the Czech population sample.

The relationship between gender and EI is subject to ongoing debate. While some models and early studies hypothesize a greater inclination among young males (Vasilescu, Crivoi & Munteanu, 2025), contemporary research often shows a shift toward parity in intent. Studies have found no significant gender differences in overall levels of entrepreneurial intention or across the three key TPB factors (AAB, SN, PBC), (Contreras-Barraza et al., 2021). Where differences persist, they often stem from socio-cultural perceptions or internalized beliefs about the entrepreneurial role, such as the perception that entrepreneurship aligns more closely with a "masculine" personality style (Deng & Wang, 2023).

The observed lack of significant gender difference in EI (p=0.567) in our research aligns with the findings of regional studies, including those within the European context, which suggest a growing convergence toward parity in intent (Contreras-Barraza et al., 2021). This outcome suggests that in the Czech Republic, the pre-behavioral barriers related to perceived social pressure (Subjective Norms) or internalized capability (PBC) are not significantly higher for women than for men. This parity indicates a healthy socio-cultural environment where, unlike some contexts where women may internalize a bias against the "masculine" entrepreneurial identity (Zisser et al., 2019), general intent is balanced. Policy focus should therefore not be primarily aimed at addressing a gender gap in initial desire, but rather at ensuring gender parity in access to resources required for the actual venture launch phase.

Age (RQ 4) – Quantitative Variable (Logistic Regression for Age)

Age was analyzed using logistic regression, allowing for the precise quantification of its impact on the probability of reporting entrepreneurial intention. The model confirmed a highly statistically significant effect for the age variable (z = -3.521), with a p-value of <0.001 (see Table 5).

Table 5. Model Summary Logistic Regression for Age

Model	Deviance	AIC	BIC	df	X^2	p
H_0	1.513	1.515	1.520	1.095		
H_1	1.500	1,504	1.514	1.094	12.58	< .001

Coefficients

	Estimate	Standard Error	z	p
(Intercept)	0.479	0.190	2.518	.012
vek	-0.015	0.004	-3.521	< .001

Source: own research

The influence of age on entrepreneurship is often viewed through a life-cycle perspective, mediated by accumulated human capital, self-efficacy, and Future Time Perspective (FTP). Younger cohorts are generally more inclined toward the initial transformation stage—opportunity identification—due to greater risk-willingness and an extended FTP (Zhang, Stough & Gerlowski, 2022). Empirical studies consistently support that age affects entrepreneurial intention, frequently showing a negative correlation, particularly among younger adult samples. The confirmed, and highly quantified, negative relationship between age and entrepreneurial intention in the CR sample robustly confirms the life-cycle perspective established in global literature (Wang, et al., 2018; Zhao et al., 2005, Martínez-González, et al., 2019).

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The quantitative measure of decline (1.489% per year) confirms that the intrinsic entrepreneurial impulse toward starting a business, driven by high future time perspective and risk willingness, peaks early and occurs early in the working life.Table 6 synthesizes the results, clearly identifying age as the critical factor affecting entrepreneurial intention in the Czech Republic, while rejecting the influence of gender and educational characteristics.

Table 6. Summary of Empirical Results (CR Data): Impact of Demographics on Entrepreneurial Intention

Independent Variable	Statistical Test Used	Test Statistic / z-value	p-value	Effect Direction / Odds Ratio (OR)	Statistical Significance (α=0.05)
Highest Education	Chi-Squared Test	10.41 (df=6)	0.108	Not Proven	Non-Significant
Gender	Chi-Squared Test	0.328 (df=1)	0.567	Not Proven	Non-Significant
Economic Focus	Chi-Squared Test	0.796 (df=1)	0.372	Not Proven	Non-Significant
Age	Logistic Regression	z = -3.521	<0.001	Negative (OR = 0.98511)	**Highly Significant**

Source: own research

The empirical results from the Czech Republic provide a complex picture, highlighting both convergences with, and critical deviations from, international entrepreneurial theory, necessitating a careful discussion of institutional and latent factors.

This finding carries significant implications for national strategy. The statistical strength of this factor confirms that policies intended to stimulate nascent entrepreneurship should be heavily focused on young adults, as they are most receptive to identifying new opportunities and converting this desire into intent (Wang et al., 2018). The sharp decline in intent over the lifespan suggests that efforts to encourage entrepreneurship among older cohorts must shift focus—away from generating novel intent and toward leveraging their accumulated capital for venture evaluation, acquisition, or expansion, recognizing their declining intrinsic motivation for high-risk creation.

The Undeniable Influence of Latent Variables: Family Entrepreneurial Background and International Exposure

The high incidence of Family Entrepreneurial Background among the surveyed population (58.12%) provides a critical contextual layer.

International evidence dictates that this factor is a powerful positive predictor of EI, often providing essential role modeling, tacit knowledge transfer, and access to capital that formal schooling lacks (Lindquist, Sol & Van Praag, 2015).

Considering the demonstrated weakness of the formal educational system and economic background (previous sections), the high prevalence of Family Entrepreneurial Background likely acts as a crucial compensatory mechanism in the Czech entrepreneurial ecosystem. The informal acquisition of human capital and social validation through family role models sustains a baseline level of entrepreneurial desirability and feasibility that would otherwise be severely depressed by the perceived inadequacy of formal training. This observation suggests that latent factors—those not explicitly tested as independent variables—may be overriding the effects of poor institutional inputs.

Similarly, while not explicitly measured against EI in the CR data, international experience is globally recognized for fostering human and financial capital (Wassink, 2020). This exposure, often associated with elevated risk tolerance and a greater need for achievement (Vandor, 2021), likely contributes significantly to the latent pool of entrepreneurial motivation, offering another channel for human capital accumulation beyond the domestic educational system.

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Conclusions

The empirical investigation into demographic determinants of entrepreneurial intention in the Czech Republic revealed a singular, dominant influence: age, which negatively impacts EI with a quantified decline of 1.489% per year. Conversely, gender and educational attainment, including specialized economic education, demonstrated no statistically significant link to intention.

Our research study validates the universal life-cycle theory of entrepreneurial motivation within a CEE transition economy. The non-significance of education highlights a structural failing in the institutional mechanisms designed to cultivate entrepreneurial capital. This implies that the Czech ecosystem relies heavily on informal, latent factors—such as Family Entrepreneurial Background – to compensate for the inadequate transfer of practical skills and confidence from formal educational channels.
Based on the confirmed relationships and identified structural anomalies, the following policy recommendations are proposed:

1. *Implement Age-Segmented Support*. Given the rapid decline in intention after young adulthood, resource prioritization must focus on targeted support for individuals in the early stages of their career, matching their high-risk appetite. Furthermore, dedicated programs should assist older, capital-rich cohorts in leveraging their experience for stable ventures, such as acquiring or scaling existing small businesses, rather than focusing on novel startup creation.
2. *Overhaul Entrepreneurship Education (EE) Curricula*. The null effect of economic education requires a systemic review of pedagogical methods. Kondrla et al. (2023) claim, the starting point is a reflection on the philosophical background of education as a repetition and production of the same. We should learn from examples of best practice, identify successful strategies that can be adapted or replicated in their own conditions (Kučera et al., 2024). EE programs must transition from theoretical instruction to applied, experiential learning, mandatory practical mentorship, and venture simulation exercises. The objective is to genuinely improve Perceived Behavioral Control (PBC) and risk management capabilities.
3. *Formalize and Leverage Family Entrepreneurial Background (FEBB).* Policymakers should recognize FEBB as a powerful, latent propeller of EI to formalize the tacit knowledge and skills transferred informally, thereby maximizing this robust intergenerational capital.
4. *Incentivize Return-Migrant Entrepreneurship*. The positive correlation between international mobility and entrepreneurial propensity suggests that specific initiatives should be developed to attract Czech citizens who have acquired extensive work experience abroad. By offering fast-track support and capital access, the nation can capitalize on the elevated human and financial capital, and higher risk tolerance, brought back by these returnees.

A limitation of this research is its reliance on general demographics, which serve as proxies rather than direct measures of the core cognitive drivers (AAB, SN, PBC). Furthermore, targeted qualitative studies are necessary to specifically diagnose the content and quality failures within the Czech educational system to determine the precise barriers preventing successful skill transfer and the cultivation of entrepreneurial conviction.

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GREEN HUMAN RESOURCES MANAGEMENT IN AGRI-ENVIRONMENTAL SECTOR: CASE FROM SERBIA*

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Abstract. Green human resources management (GHRM) is becoming increasingly important for improving ecological sustainability, especially in the agri-environmental sector, but its application and effect are still under-researched. Because of this, this study investigates the perception and impact of GHRM practices in the agro-ecological sector in the Republic of Serbia using a mixed-methods approach. For this purpose, data were collected from 203 respondents from the public and private sectors, while quantitative data were analysed using the NVivo coding method and thematic mapping. Applied descriptive statistics, t-test and regression show that agri-environmental private organisations are more integrated with GHRM than public organisations ($t=2.98$; $p<0.01$). The results of regression analysis significantly confirm environmentally oriented behaviour of employees ($\beta=0.632$; $p<0.001$), explaining 46.8% of variance. Nvivo analysis extracts the six main thematic fields: green recruitment, training, performance appraisal, awarding, organisational culture, and outcomes. The results indicate strong dedication of organisations to environmental responsibility and highlight the importance of a qualitative and quantitative approach toward sustainable-oriented human resources management in the agri-environmental sector in Serbia.

Keywords: green human resources management; agri-environmental; agro-ecological; mix-method approach

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JEL Classifications: O15, Q13, J24

1. Introduction

In modern society, there is a growing need to reach sustainability goals, which include adjusting the economic development pillar with environmental protection. Sustainable development considers a balance between economic, social and environmental priorities. Raising public environmental awareness and international environmental policies encourage organisations to adopt practices that are environmentally responsible. In this

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process, people play a key role, as their knowledge, behaviour, and values directly contribute to achieving sustainability goals (Šepa et al., 2024; Usman et al., 2025).

Contemporary human resources management has overcome traditional tasks such as recruiting (Kambur & Yildirim, 2023) or training (Ma, 2023). A new approach known as green human resources management connects and integrates human resources management with environmental protection goals (Al-Minhas et al., 2020; Campos-García et al., 2025). GHRM includes environmentally oriented hiring and training related to environmental protection, as well as employees' achievements evaluation based on green criteria and awarding sustainable behaviour. These practices help organisations reduce their negative ecological impact and encourage employees to act more responsibly towards the environment.

Globally, GHRM practices are becoming recognised by the agri-environmental sector as an efficient way to improve sustainable agricultural production and raise employees' awareness. Within the agro-ecological sector in the Republic of Serbia, which includes agriculture, food production, and additional environmental activities, the application of the GHRM approach has a significant impact. Recognising that this sector is directly dependent on natural resources, environmentally oriented management is crucial for long-term sustainability. However, GHRM studies, particularly in this context, remain limited. This research contributes to the advancement of knowledge by examining the application of GHRM in Serbia's agro-ecological sector. This area has been under-researched to date, and provides empirical evidence on how environmentally oriented HR practices influence employee behaviour in terms of environmental protection. Based on this fact, this research aims to examine the extent of GHRM application and practices, as well as their impact on the ecological responsibility of employees in the agri-environmental sector.

2. Theoretical background

The concept of sustainable human resources management was developed as a part of the broader context of corporate sustainability. This concept integrates economic, social and environmental goals into human resources management policies and practices (Cheema & Javed, 2017). Over time, the concept of sustainable development was extracted to form a new, focused, and more specific concept: green human resources management (GHRM) (Nikolova & Yordanova, 2023). The GHRM concept connects activities in the field of human resources with ecological goals, encouraging organisations to promote environmentally responsible behaviour among employees (Adu Sarfo et al., 2024). Numerous studies have focused on GHRM in industry, and only recently has research been conducted in the environmentally oriented sector (Yong et al., 2020).

The main dimensions of GHRM include green recruitment and selection, where organisations choose candidates who share environmental values. Green training and development help employees to build knowledge and skills related to environmentally oriented activities. Green performance appraisal evaluates employees based on ecological criteria (AlKetbi & Rice, 2024). Previous studies have consistently highlighted that training and development are key drivers of green management, as they enable employees to adopt practices that reduce waste, utilise resources rationally, and address environmental problems (Ali et al., 2020). Additionally, green rewards and recognition encourage environmentally responsible behaviour through financial or symbolic incentives. A green organisational culture promotes shared values and a collective sense of ecological responsibility (Cheema & Javed, 2017; Sahoo et al., 2025). Previous studies have shown that these practices can improve organisational performance and yield better environmental results (Pham et al., 2020; Shah and Soomro, 2023). GHRM facilitates the creation of an environment where employees share similar attitudes towards sustainability (Mićović, 2025). Also, GHRM outcomes include higher environmental awareness and job satisfaction (Baykal et al., 2023; Ostojić et al., 2025), as well as more pro-environmentally focused behaviour (Omarova & Jo, 2022) and better organisational reputation (Wang et al, 2023) and sustainability performance (Ignjatović et al., 2025). In the literature, employee green behaviour is defined as intentional, work environment-specific pro-environmental actions that contribute to reducing negative environmental impacts and is recognised as a key strategy for organisations to improve environmental performance and achieve sustainability goals (Chaudhary, 2019; Sabokro et al., 2021).

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In the agricultural and agri-environmental sector, GHRM plays a special role due to the natural resources on which it depends. Sustainable HR practices help minimise environmental risk, increase resource efficiency, and raise employees' awareness (Sharma & Singh, 1997; Ma et al., 2023), as training and education are crucial for the agri-environmental sector (Nikolova & Yordanova, 2023). However, the application of green HR practices in the agri-environmental sector faces various challenges, including limited financial resources, seasonal employment, and a lack of ecological training (Singh, 2022). Recent studies highlight the need for stronger institutional support and higher management dedication to sustainability in the agri-environmental sector (Pandey et al., 2025). The review of literature related to GHRM in the agri-environmental sector suggests that these practices hold significant importance for the sustainable development and ecological responsibility of agricultural institutions (Aftab et al., 2023). Recent studies have mainly focused on key dimensions of GHRM, including green employment and selection, training and development of employees, performance assessment based on ecological criteria, green awards and recognitions, as well as an organisational culture that supports sustainability (Xue et al., 2025).

Some studies emphasise that it is essential to adopt GHRM strategies to specific conditions in the agri-environmental sector, such as local environmental challenges and current regulations. Some other studies examined the relationship between GHR policies, employees' satisfaction and the organisation's reputation (e.g., Zhang et al., 2025). Overall, the available literature suggests that GHRM can be a significant tool for promoting sustainable business in agriculture and environmental protection. However, it also indicates that more empirical research is needed to precisely assess the impact of individual practices on ecological and organisational outcomes.

Several empirical studies have measured the effects of GHRM practices in the agro-ecological sector. For example, research conducted in Pakistan employed quantitative methods, including regression, ANOVA, and t-tests, to examine the impact of GHRM practices in the agricultural industry (Cheema & Javed, 2017). The results demonstrated a strong correlation between the application of GHRM practices and the enhancement of sustainable agricultural practices. However, the survey also revealed that employees have a limited understanding of GHRM, indicating the need for additional education and training. Additionally, research conducted on a sample from Taiwan (Hooi et al., 2022), which applied rigorous statistical techniques such as confirmatory factor analysis, correlation analysis, structural modeling, and bootstrapping, showed that GHRM significantly influences green organisational citizenship behaviors, with green culture mediating this relationship and green value attitudes further amplifying the effect – thus confirming the specific mechanisms through which GHRM shapes pro-environmental outcomes.

Similarly, research conducted in Indonesia has shown that GHRM practices have a significant impact on employee environmental behaviour (Subyantoro et al., 2022). Based on data from 510 participants, the study confirmed that GHRM encourages pro-environmental behaviour among employees, which contributes to the organisation's better overall environmental performance. These quantitative studies provide evidence of the effectiveness of GHRM in the agro-ecological sector, but also point to the need for additional studies that would more precisely measure the impact of individual practices on environmental and organisational outcomes.

Although numerous studies have studied GHRM in the industrial and service sectors, works dealing with the agro-ecological sector in Southeast Europe are still few. In developing countries, the implementation of GHRM faces significant economic, political, and sociocultural challenges, which is why green practices are often limited to a few departments or organisations, highlighting the need for additional research and strategies tailored to the specific context of these countries (Kodua et al., 2022). In Serbia, many organisations are just beginning to apply green HRM principles. Therefore, this paper aims to fill the research gap by combining a quantitative and qualitative approach to examine the level of application of GHRM practices and their impact on the environmental behaviour of employees in the Serbian agro-ecological sector.

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3. Research objective and methodology

3.1 Dataset description

This research employs a combined methodological approach, integrating quantitative and qualitative methods to examine the application and impacts of green human resource management (GHRM) in Serbia's agro-ecological sector. The quantitative part of the research is based on the frameworks used in earlier studies (Kuo et al., 2022; Singh, 2022; Alshehri et al., 2024), while the qualitative part relies on thematic analysis, utilising NVivo 15 software. These methods were chosen to provide both statistical confirmation of the relationship between the variables and a deeper understanding of how GHRM is understood and applied in this specific context.

Respondents from various areas of the agricultural and agro-ecological sector participated in the research, including agrarian enterprises, agritourism facilities, agricultural and environmental non-governmental organisations, local government departments responsible for rural development and environmental protection, agricultural advisory services, and registered family farms. To ensure diversity and representativeness, organisations from both the public and private sectors were included in the sample. A total of 230 questionnaires (electronic and personal) were distributed in the period 2022–2024, and 203 valid answers were retained for analysis. The final sample consisted of 146 respondents from the private sector and 57 from the public sector.

The questionnaire is based on Singh (2022) and adapted to the Serbian context. It consists of 20 statements that examine the relationship between sustainable HRM practices, the environmental behaviour of employees and their job satisfaction in agricultural and environmental organisations. The first part of the questionnaire collects basic demographic data, including gender, age, education, and job position. The second part contains statements about GHRM practices, rated on a five-point Likert scale (1 - strongly disagree to 5 - strongly agree). Participation was voluntary, and all responses were anonymous to protect the privacy of respondents.

3.2 Statistical tools and techniques

Quantitative data were analysed using SPSS 26.0 software. Descriptive statistics were used to present sample characteristics and main variables, while reliability analysis (Cronbach's alpha) checked the internal consistency of the GHRM constructs. Pearson's correlation analysis was applied to determine the relationship between the dimensions of GHRM, environmental behaviour and job satisfaction. Differences between the public and private sectors were examined using independent samples t-tests. At the same time, multiple regression analysis was employed to determine the predictive impact of GHRM practices on employee environmental behaviour, controlling for demographic and organisational factors. All statistical tests were conducted at a significance level of 5% ($p < 0.05$).

In the qualitative part of the research, a thematic content analysis was carried out using NVivo 15 software, in order to complement the quantitative findings. The participants' open-ended comments and textual data were coded and organised into thematic units reflecting the main aspects of GHRM. The analysis was conducted through stages of open, axial and selective coding, which led to the identification of six dominant thematic categories: green recruitment and selection, green training and development, green performance appraisal, green rewards and recognition, green organisational culture and outcomes of GHRM practices. The NVivo dendrogram and code frequency matrix showed how employees perceive and rank these dimensions in their daily work. These qualitative insights enriched the statistical results, providing a more complete understanding of how GHRM contributes to sustainability in Serbia's agro-ecological sector.

4. Results and discussion

Table 1 presents the demographic and organisational characteristics of the respondents (n = 203). Most of the participants worked in the private sector (72%), while 28% were employed in the public sector. The majority of respondents came from small and medium-sized agricultural enterprises, with 45.3% working in organisations with less than 10 employees. When it comes to gender, 54.2% of the participants are women, 44.8% are men, while 1% marked "other". The average age of the respondents was approximately 43.5 years (SD = 11.5), indicating a mature and experienced workforce (Leković et al., 2025). Regarding job positions,

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almost half of the respondents (49.8%) were operational employees, 35% were managers, and 15.3% were workers in HR sectors.

Table 1. Sample characteristics (n=203)

Variable	Categories	Frequency	Percentage (%)
Sector	Public	146	72.0
	Private	57	28.0
Organisation size	Small	92	45.3
	Medium	71	35.0
	Large	40	19.7
Role	HR	31	15.3
	Manager	71	35.0
	Operational staff	101	49.8
Gender	Female	110	54.2
	Male	91	44.8
	Other	2	1.0
Age	Mean	(≈ 43.5)	(≈ 11.5)

Source: Authors' calculation

4.1 Descriptive statistics and reliability analysis

Table 2 shows descriptive statistics and internal consistency coefficients for all components used in the study. Cronbach's alpha values for each dimension of the GHRM were above the recommended limit of 0.70, which confirms the satisfactory internal reliability of the measurement scales. Among the analysed dimensions, Green organisational culture (M = 3.35, SD = 0.73) and Green training and development (M = 3.25, SD = 0.71) achieved the highest average values, indicating that organisations in the Serbian agro-ecological sector have made significant progress in promoting ecological values and strengthening employee capacities. Similar results were reported by Pham et al. (2020), emphasising that environmental training and a supportive green culture are among the most important factors that shape the ecological behaviour of employees in organisations. In contrast, Green Awards and Recognition achieved the lowest average score (M=2.90, SD=0.80), suggesting that the mechanisms to encourage sustainable behaviour are still limited. As indicated by Paillé & Raineri (2015), reward systems often remain the weakest component of GHRM implementation because environmental performance is still rarely linked to formal compensation structures. The combined GHRM index (M = 3.11, SD = 0.58) indicates a moderate level of application of green HRM practices in the surveyed organisations, suggesting that organisations are still in the process of transitioning to HR policies that are more oriented towards sustainability.

Table 2. Descriptive statistics and reliability of scales

Components	Items	Mean	SD	Min	Max	Cronbach's α
Recruitment	4	3.05	0.68	1.00	5.00	0.75
Training and development	4	3.25	0.71	1.00	5.00	0.78
Performance appraisal	4	3.00	0.74	1.00	5.00	0.72
Rewards and recognition	3	2.90	0.80	1.00	5.00	0.70
Green culture	4	3.35	0.73	1.00	5.00	0.79
GHRM overall	5	3.11	0.58	1.80	4.60	0.82
Environmental behaviour	3	3.30	0.68	1.00	5.00	0.77
Job satisfaction	3	3.10	0.72	1.00	5.00	0.74

Source: Authors' calculation

4.2 Correlation analysis

As shown in Table 3, all dimensions of green HRM were positively and significantly correlated with one another ($p < 0.01$). The strongest relationships were observed between Green Culture and Training and Development (r=0.62), as well as between Green Culture and the overall GHRM index (r=0.75). In addition, the overall GHRM index is significantly related to both the environmental behaviour of employees (r=0.60) and job

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satisfaction (r=0.50). These results suggest that organisations with more developed green HR practices have employees who demonstrate more environmentally responsible behaviour and report higher levels of job satisfaction. The findings are consistent with previous research (e.g. Yusoh et al., 2024), highlighting the role of GHRM in shaping pro-environmental behaviour in the workplace.

Table 3. Correlations among key dimensions (Pearson's r)

Variable	1	2	3	4	5	6	7	8
Recruitment	1.00							
Training and development	.55**	1.00						
Performance appraisal	.48**	.52**	1.00					
Rewards and recognition	.40**	.45**	.42**	1.00				
Green culture	.60**	.62**	.58**	.50**	1.00			
GHRM overall	.58**	.65**	.60**	.53**	.75**	1.00		
Environmental behaviour	.45**	.50**	.48**	.42**	.55**	.60**	1.00	
Job satisfaction	.35**	.38**	.36**	.30**	.45**	.50**	.62**	1.00

Source: Authors' calculation

4.3 Differences between the private and public sectors

Table 4 presents the results of a t-test for independent samples, conducted to assess the differences in the perception of GHRM practices between respondents from the public and private sectors of the agro-ecological sector. The results of Levene's test for equality of variances (F=1.23, p=0.27) show that the assumption of equal variances is satisfied. The t-test revealed a significant difference between the two sectors (t = -2.98, p = 0.003), indicating that the perception of GHRM practices differs significantly. Specifically, respondents from the private sector reported a higher level of application of GHRM practices compared to those in the public sector. These results suggest that the private sector in Serbia is more proactive in adopting HR strategies aimed at environmental protection, which may be a consequence of increased market pressure, heightened competition, and compliance with sustainability certification requirements.

Table 4. t-Test: differences in GHRM overall between private and public sectors

Levene's test for equality of variances	t-Test for equality of means				
	F	Sig.	t	df	Sig.(2-tailed)
Equal variances assumed	1.23	0.27	-2.98	201	0.003
Equal variances not assumed			-2.96	199.6	0.004

Source: Authors' calculation

4.4 Regression analysis

The results of the regression analysis, shown in Table 5, indicate that the model is statistically significant ($F(5,197) = 43{,}361$, $p < 0.001$) and explains 46.8% of the variance in employees' environmental behaviour ($R^2 = 0.468$). This suggests that green human resource management (GHRM) practices are a strong predictor of employees' pro-environmental behaviour in the agro-ecological sector of Serbia. The coefficient for the overall GHRM index ($B = 0.528$, $\beta = 0.632$, $p < 0.001$) indicates that a greater application of GHRM practices leads to a significant increase in environmentally responsible behaviour. In other words, organisations that consistently apply green principles in hiring, training, performance evaluation and rewarding have employees who are more actively involved in pro-environmental activities. The control variables, large size (B=0.221, p=0.025) and manager role (B=0.186, p=0.020), showed a significant but moderate effect, suggesting that larger organisations

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and managers are more likely to exhibit environmentally responsible behaviour compared to smaller organisations and operational employees. Medium-sized companies and the role of operating employees had no significant effect ($p > 0.05$). Overall, the results confirm that GHRM practices have a positive and considerable influence on the development of environmental awareness and employee behaviour in the agro-ecological sector. Similar results were also recorded in other sectors, such as the chemical industry (Kuo et al., 2024) and the hotel industry (Alshehri et al., 2024).

Table 5. Regression analysis: predicting environmental behaviour

Variable	B (unstand.)	SE	β (stand.)	t	p
Constant	1.80	0.45	-	4.00	<0.001
GHRM overall	0.45	0.08	0.52	5.63	<0.001
Medium size (vs. small)	0.10	0.07	0.12	1.43	0.15
Large size (vs. small)	0.15	0.09	0.14	1.67	0.10
Role manager (vs. HR)	0.08	0.06	0.10	1.33	0.18
Role operational (vs. HR)	0.05	0.05	0.07	1.00	0.32

Source: Authors' calculation

Compared to a study (e.g., Singh, 2022) that investigated sustainable HRM practices in the agricultural industry and showed high average values (above 4.0) for most statements, the results of this study indicate a more moderate level of GHRM implementation in Serbia (total M=3.11). Although both studies emphasise the importance of employee training and effective work management, the agro-ecological sector in Serbia still faces challenges in reward systems and management support, indicating that sustainable HRM is still in its early stages of development.

4.5 Qualitative analysis – structure of GHRM practices in the agro-ecological sector of Serbia

Qualitative analysis conducted using the NVivo tool shows an integrated approach that connects HR practices with environmental and sustainable goals of organisations. The analysis identified the key dimensions of GHRM practices in Serbia's agro-ecological sector. Green recruitment and selection emphasise environmental competencies during employment, including the inclusion of environmental responsibility in job descriptions and the application of ecological criteria in the selection of candidates. This approach ensures that employees value environmental awareness and prefer candidates who share the organisation's ecological values . Green training and development aim to increase environmental awareness through workshops, continuous learning programs, and skills improvement initiatives with a focus on sustainability. Respondents reported greater awareness of energy efficiency and the integration of environmental protection topics into all training. Green performance assessment incorporates environmental performance indicators and sustainability targets into employee KPIs, providing feedback on environmental activities. Supervisors evaluate both productivity and environmental impact, motivating employees to take sustainability seriously. Green rewards and recognitions include environmental bonuses, recognition programs such as "Green Employee of the Month," and non-material rewards. Employees pointed out that motivation increases when environmental contributions are recognised, and even rare financial rewards for green ideas effectively encourage sustainable behaviour. A green organisational culture reflects common environmental values, as exemplified by leaders and collective norms. Respondents emphasised that environmental protection is embedded in the organisation's mission, managers lead by example, and teamwork encourages responsibility for reducing waste and energy consumption.

The results of implementing GHRM practices show that employees actively participate in pro-environmental behaviour, report greater job satisfaction, and perceive an improvement in the organisation's reputation. Participants also emphasised a stronger commitment to sustainability and greater engagement after implementing these practices.

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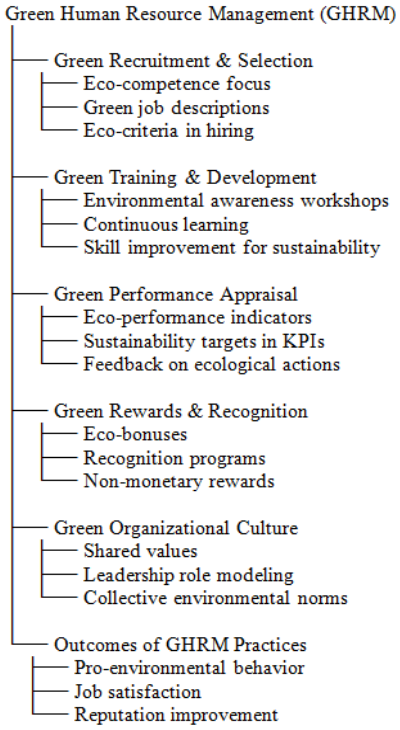


Figure 1. Dendrogram GHRM in the agri-environmental sector
Source: *Authors*

A total of 367 references were coded from the text data, including respondents' responses, open-ended comments and NVivo project documents. The highest frequencies were recorded for Green organisational culture (17.6%), Outcome of GHRM practices (18.9%), and training and development (15.3%), which shows that participants most emphasised the importance of organisational culture, training, and the visible results of GHRM policies. The Green Awards and Recognition segment (7.5%) was the least mentioned, which confirms the quantitative findings that motivational mechanisms in this area are still insufficiently developed. Qualitative findings explain how respondents in the Serbian agro-ecological sector experience and apply GHRM practices. Analysis in NVivo showed that most participants associated GHRM with environmental awareness, collaboration and personal responsibility at work. Green culture and training were the most common topics, which confirms that employees consider knowledge and shared values as key to sustainable behaviour. These findings are consistent with previous research that has sought to theoretically explain the link between GHRM practices and environmental outcomes, most often highlighting green selection, training, performance management, employee rewards and empowerment as key mechanisms through which organisations develop sustainable behaviour (Masri & Jaaron, 2017). Respondents also highlighted problems such as a lack of resources, weak incentives, and limited management support, indicating that the implementation of GHRM practices is still developing.

Table 6. Frequency of code and subcodes

Codes	Subcodes	Number of references	Percentage of total (%)
Green recruitment and selection	Eco-competence focus	21	4.7
	Green job descriptions	17	3.8
	Eco criteria in hiring	15	3.3
subtotal		53	11.8
Green training and development	Raising environmental knowledge	28	6.2
	Continuous learning	23	5.1
	Improvement skills for sustainability	18	4.0
subtotal		69	15.3
Green performance appraisal	Eco. Performance indicators	19	4.2
	Sustainability targets	16	3.6
	Feedback on eco. actions	12	2.7

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subtotal		47	10.5
Green rewards and recognition	Eco bonuses	14	3.1
	Recognition programs	11	2.4
	Non-monetary rewards	9	2.0
subtotal		34	7.5
Green organisational culture	Shared values	31	6.9
	Leadership role	26	5.8
	Collective environmental norms	22	4.9
subtotal		79	17.6
GHRM practices outcomes	Pro-environmental behavior	33	7.3
	Job satisfaction	27	6.0
	Reputation improvement	25	5.6
subtotal		85	18.9

Source: Authors' calculation

These results are consistent with the findings of other qualitative studies in the agricultural sector. Singh (2022) and Jeyasree (2023) have highlighted that the implementation of green HRM in agriculture depends on the commitment of leaders and institutional capacity. Pham et al. (2020) also found that environmental awareness is often higher than actual implementation, especially in developing contexts. Recent qualitative studies confirm that sustainability in agriculture requires better-structured policies and the active involvement of workers (Zahoor & Gerged, 2021; Sørensen et al., 2021). Overall, this research supports the view that the Serbian agro-ecological sector is at an early but promising stage of integrating green HRM principles into everyday practice. According to the fact that GHRM is a trend and necessity, the results of our research confirm that it is precisely GHRM practices – from green hiring to training, rewards and development of environmental competencies – that represent the central mechanism through which organisations truly operationalise the principles of sustainable business.

5. Conclusion

This research examined the implementation of green human resource management (GHRM) practices in Serbia's agro-ecological sector. The results showed a moderate level of GHRM implementation, with the strongest areas being green organisational culture and employee training, while green rewards and recognition were the least developed. Regression analysis confirmed that GHRM practices have a positive influence on employees' green behaviour, indicating that the implementation of green HRM principles can help organisations become more environmentally responsible. The novelty of this research is reflected in the fact that it represents one of the few empirical analyses of GHRM practices in Serbia's agro-ecological sector, demonstrating how certain human resource management activities influence the environmentally responsible behaviour of employees in a context that has been relatively understudied. This fills a significant gap in the literature. The application of advanced statistical methods (e.g., factor analysis, regression models, and testing of relationships between variables) enabled the identification of specific HR practices that have the greatest impact on employees' pro-environmental behaviour.

The research has some limitations. The sample consisted exclusively of 203 respondents from Serbia, so the results may not accurately reflect the situation in other regions. The data were collected on a self-report basis, which may be subjective. Future research should include more countries, utilise data collected over a longer period, and focus on the roles of managers, institutions, and digital tools in supporting the implementation of GHRM in agricultural and ecological organisations. The added value of this research lies in its high replicability, since the applied methods are clearly defined and can be used in future studies in a similar context.

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CORPORATE TAX RATES IN THE EUROPEAN UNION: CONVERGENCE PECULIARITIES*

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Abstract. This paper analyses the convergence dynamics of statutory and effective corporate income tax rates within the European Union (EU) from 2004 to 2023, with the goal of determining whether member states are moving toward a single common tax level or forming several stable convergence clubs. The study employs the Phillips–Sul club convergence methodology, which captures heterogeneous transitional paths and facilitates the identification of country groups that share similar long-term tax trajectories. Using a balanced panel of 27 EU member states and data from the European Commission and the Centre for European Economic Research (ZEW), we test for both overall convergence and club patterns. The global log-t test rejects the hypothesis of overall convergence for both statutory and effective tax rates. The strongly negative test statistics ($t = -8.33$ for statutory rates and $t = -8.29$ for effective tax rates) confirm the existence of multiple long-term regimes rather than a unified convergence pattern. Statutory tax rates separate into three distinct clubs, reflecting different strategic approaches to statutory taxation across member states. Effective tax rates form two more cohesive clusters, with the group of low-ETR economies demonstrating the strongest internal convergence and the most consistent long-run dynamics. Robustness checks across alternative specifications support these findings. Overall, the results indicate that the EU does not follow a uniform path toward complete tax harmonisation. Instead, European corporate taxation is evolving toward the coexistence of several stable fiscal regimes, suggesting that spontaneous convergence remains limited despite ongoing economic integration.

Keywords: statutory tax rates; effective tax rates; convergence; tax harmonisation; Phillips-Sul club convergence

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JEL Classifications: H25, H71, F38, O52

1. Introduction

Over the past two decades, tax harmonisation has become one of the central issues in the European Union's economic integration. The EU's enlargement, the globalisation of capital flows, and the growing mobility of multinational companies have created an environment where differences in tax rates and tax bases have turned into an important element of economic competition among member states. While the statutory corporate tax rate remains a visible and politically sensitive part of national fiscal systems, the effective tax rate (ETR) has gained increasing relevance, as it captures the real tax burden

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after accounting for deductions, exemptions, and investment incentives. Although theoretical models of European integration anticipate a gradual convergence of tax rates toward a common equilibrium level, empirical evidence shows that this process is neither linear nor uniform (Vicente, 2025). Since member states retain a high degree of fiscal sovereignty, regional and structural clusters of countries with similar tax policies tend to emerge (van Ganzen, 2025). Such clusters may result from coordinated harmonisation efforts or, conversely, from competitive pressures within the single market. Effective tax rates often reveal even bigger differences than statutory rates, as they reflect the actual design of tax systems and specific regimes. The structure of EU finances reveals that the European Union already possesses several forms of revenue capacity, including own resources that, in practice, operate as taxing powers, as well as a wide range of off-budget instruments, such as borrowing through the European Investment Bank and the European Commission. Various pooling arrangements, transfers and guarantees further strengthen the fiscal role of the EU centre, indicating that the EU functions with a real fiscal capacity rather than acting only as a spender without meaningful revenue authority (Groenendijk, 2023).

Following the 2004 enlargement, when Central and Eastern European countries joined the EU, the key question became whether this expansion strengthened or weakened tax convergence. Many of the new member states reduced their corporate tax rates to attract foreign investment and improve competitiveness, often introducing preferential tax regimes that later influenced their effective taxation levels. In contrast, older member states, such as Germany, France, or Belgium, maintained higher and more stable tax rates, which preserved notable differences across the EU. Changes in the design of corporate income tax systems in several EU member states, especially the shift from discriminatory imputation systems to shareholder relief systems, changed the relative tax burden on domestic and cross-border dividend income. Simulation results based on cost of capital and effective average tax rates show that abolishing imputation systems removed the tax advantage for domestic investments and increased competitive pressure, making affected countries less attractive relative to foreign investment locations (Fischer, Müller & Spengel, 2023). EU efforts to limit harmful tax competition are constrained because the Code of Conduct and state aid rules cannot clearly address the incentives that drive aggressive tax planning, which is why a Common Consolidated Corporate Tax Base is proposed as a more effective solution (Perotto, 2021).

In this context, it is essential to examine whether tax rates across the EU converge as a whole or whether countries form smaller, homogeneous groups, known as convergence clubs. The analytical framework for this type of research is provided by the club convergence methodology developed by Phillips and Sul (2007, 2009), which captures heterogeneous dynamics and identifies countries with similar trajectories. Unlike traditional β-convergence or σ-convergence tests, which assume a single common trend, the Phillips–Sul approach allows for multiple equilibrium paths and helps determine whether economies converge within smaller groups. This approach is suitable for analysing both statutory and effective tax rates, the latter often displaying even greater heterogeneity.

Our study aims to identify the existence and nature of convergence clubs in the statutory and effective corporate tax rates of EU member states between 2004 and 2023. The results will provide an empirical view of how tax policy evolved during a period marked by major fiscal reforms, financial crises and regulatory initiatives, including OECD's BEPS actions and EU anti-avoidance directives. At the same time, they will help clarify whether the European tax landscape is moving toward deeper harmonisation or persistent segmentation and thus contribute to a better understanding of the limits and opportunities of fiscal integration within the EU.

2. Theoretical Background

The concept of convergence originates in Solow's neoclassical growth model, which posits that economies with similar fundamental parameters tend to converge toward the same long-term growth rate, while income differences persist if their structural characteristics differ (Solow, 1956). This

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framework was later extended to the fiscal sphere, especially to the study of tax burden convergence and the evolution of tax systems. Within the European Union, the question of tax convergence is particularly important because member states share a single market but retain autonomy in setting tax rates, bases and reliefs, creating constant tension between harmonisation and tax competition.

Traditional approaches to measuring convergence include beta convergence and sigma convergence. Beta-convergence assumes that countries with higher tax burdens will reduce their rates faster than those with lower burdens. Sigma-convergence focuses on how the dispersion of tax rates changes over time. However, empirical evidence shows that these approaches fall short, as they assume a single equilibrium level and homogeneous behaviour across countries, something that clearly does not reflect the European tax environment. A good example is the study by Regis, Cuestas and Chen (2015), who analysed 19 European countries from 1980 to 2014 and found no common convergence pattern in either statutory rates or broader tax burdens. Instead, they identified four distinct clusters of tax regimes. Their results also showed that differences persist despite a shared institutional setting and integration.

Fiscal systems across advanced economies show developments that, particularly after the 2007 financial crisis, tend more toward divergence than convergence. While corporate profit taxation shows signs of downward convergence, most other tax categories increasingly diverge, and the gap between liberal and high-redistribution models has widened, with European countries shifting toward the latter (Péligry & Ragot, 2024).

These findings confirm that conventional methods cannot fully capture the actual dynamics of tax systems. Income taxation in Central and Eastern European countries has followed both converging and diverging trajectories between 1995 and 2018, with many states lowering overall and corporate tax rates while the direction and speed of these adjustments shifted across EU accession, tax reform periods and the global financial crisis (Bernardelli et al., 2023).

Indicators of effective corporate taxation, as reflected in companies' balance sheets, increasingly provide a clearer picture of how much companies actually pay compared to statutory rates. Their importance has grown as better data and international tax reform discussions have highlighted the need for backwards-looking measures that reflect real tax burdens more accurately (Jansky, 2023). Studies focusing on effective tax rates add another layer of insight, as ETRs reflect the actual burden faced by companies. In their analysis of 21 OECD countries from 1982 to 1999, Devereux, Lockwood and Redoano (2008) showed that effective rates are the most sensitive to tax competition and exhibit greater variation and faster responses to changes in the economic environment than statutory rates. Subsequent work in the European context also confirms that ETRs are highly heterogeneous and shaped by economic structure, investment incentives and preferential regimes.

Emerging EU economies increasingly rely on lowering effective average tax rates to attract foreign direct investment, reflecting the tension between tax coordination and fiscal competitiveness within the single market (Bilan & Apostoaie, 2025). Long-run evidence from 1998 to 2021 indicates that lower ETR values are associated with greater FDI localisation, with adjustment speeds varying across countries, and the overall pattern suggests tax competition rather than EU-level coordination (Glavaski et al., 2023; Mose et al., 2025). Within the European Union, the decline in effective tax rates of multinational corporations between 2005 and 2015 was primarily driven by reductions in domestic statutory rates, rather than by profit shifting, which accounted for only about 1% of the overall decline among EU-headquartered firms (Garcia-Bernardo, Jansky, & Torslov, 2022). The introduction of DEBRA (Debt Equity Bias Reduction Allowance) and Pillar Two reduces the tax-driven preference for debt financing. It raises effective tax levels in low-tax countries, which limits how much DEBRA can lower the overall tax burden for firms. Their interaction leads to a convergence of effective corporate tax rates across EU member states, creating a more even competitive environment in corporate taxation (Gschossmann et al., 2025). In the V4 countries, the reinvestment of foreign direct investment profits is strongly linked to the effective corporate income tax burden and higher ETRs are associated with lower

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reinvestment rates by multinational firms. Institutional conditions related to starting a business, access to credit and contract enforcement also play a significant role, whereas broader macroeconomic factors and corporate profitability appear to have no meaningful influence on reinvestment behaviour (Procházka & Černá, 2022).

As tax systems have become more diverse, more flexible methodological tools have been needed. One of the most influential approaches is that developed by Phillips and Sul (2007, 2009), who introduced a new method of measuring convergence based on dynamic factors and transitional ratios. Their method enables the distinction between countries moving toward a common equilibrium and forming several stable clubs. A major strength of this approach is that it does not assume homogeneous behaviour or a single target level, and it can identify heterogeneous dynamics that traditional methods overlook.

Tomal (2024) provided a detailed synthesis, emphasising that the Phillips–Sul method offers the best available tools for detecting heterogeneous dynamics and performs well even with short panels, making it suitable for European tax data. Institutional changes within the EU also play a major role in shaping tax systems. The ATAD directive, the OECD's BEPS initiatives, and the debate on a global minimum rate of 15% have all influenced tax regimes, although they have not produced meaningful convergence. Van Cleynenbreugel (2019) demonstrated that EU tax harmonisation remains selective, and member states have retained substantial control over defining their tax bases despite shared rules. This space for autonomy allows different equilibria to persist and stable clusters to form. The global minimum tax establishes a minimum threshold for the tax burden that multinationals must bear, which limits certain forms of tax competition while still allowing countries to compete through grants and refundable tax credits. As a result, its overall impact on tax competition is weaker and more complex than many policymakers initially expected (Devereux & Vella, 2023).

The European tax landscape is marked by fragmentation (Hyun, 2023; Calijuri & Catinari, 2025). An empirical analysis of effective corporate tax rates in EU countries from 2013 to 2023 shows that differences are narrowing, with low-tax economies maintaining stable long-term positions and high-tax countries converging more quickly toward the average. These trends are confirmed by both beta and sigma-convergence results, which indicate gradual convergence among EU tax regimes (Uličný & Andrejovská, 2025). More vigorous tax enforcement can limit profit shifting and reduce harmful tax competition, but meaningful coordination remains difficult because low-tax countries and tax havens have little incentive to cooperate (Hindriks & Nishimura, 2021). Some EU countries may continue to compete for tax bases by quietly easing tax enforcement, even when statutory tax rates are less significant. Because weaker enforcement makes tax evasion more likely, the EU's anti-money laundering system can help reveal and limit these practices, thereby closing an essential gap in controlling tax competition (Denk, 2022).

Overall, tax convergence in the European Union is shaped by the interaction of two forces: harmonisation pressure and tax competition. Harmonisation transfers some rules into national legislation, while competition leads to diverse responses as countries use taxation as a policy tool. In such a setting, a single equilibrium is unlikely to emerge. The Phillips–Sul framework (2007, 2009) captures this fragmented dynamic, and empirical studies consistently show that tax systems converge primarily within smaller clubs rather than across the EU.

Table 1 provides a structured overview of research studies examining tax burden convergence within the European Union and in a broader international setting. Grouping the literature by methodological approach facilitates the distinction between studies that employ modern club-convergence techniques and those relying on traditional beta and sigma-convergence methods.

The first group comprises empirical analyses that employ the Phillips–Sul method or similar panel techniques to identify stable convergence clubs or clusters. These studies show that EU tax regimes do not move toward a single common equilibrium; instead, they form several long-lasting groups with

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distinct trajectories. The second part of the table summarises literature based on traditional convergence approaches, such as beta and sigma convergence. These studies demonstrate that, despite a decline in tax rates to some extent, differences between EU member states persist over the long term. Presenting these works together in one review table makes it clear how methodological approaches to studying tax convergence have evolved, while also underscoring the consistent conclusion that the European tax landscape is moving toward the coexistence of stable tax regimes rather than complete harmonisation.

Table 1. Survey of papers on tax convergence

Paper	Data	Methodological Approach	Key Results	Category
Regis, Cuestas & Chen (2015)	EU-19 & EU-25 1980–2014	Club convergence	Four clubs, no overall convergence	Club convergence
Delgado & Presno (2017)	EU-15 1975–2011	Club convergence	Several clubs in each component	Club convergence
Esteve et al. (2000)	EU-15 1967–1994	Sigma convergence, time series	Multiple countries are converging toward Germany	Traditional convergence
Uličný & Andrejovská (2025)	EU-27 2013–2023	Beta and sigma convergence analysis (ETR & statutory)	Significant β- and σ-convergence; dispersion and heterogeneity decreasing.	Traditional convergence

Source: Own processing

3. Research Objective and Methodology

This empirical study aims to examine whether, between 2004 and 2023, the European Union experienced convergence in tax burden from two perspectives: statutory corporate income tax rates and effective tax rates (ETR). Including both indicators is essential because statutory rates reflect the declared fiscal policy of each member state, while ETRs offer a more realistic picture of the actual tax burden faced by firms once allowances, tax bases and incentive structures are considered. Analysing convergence in both measures enables a more comprehensive assessment of the balance between the EU's harmonisation efforts and ongoing tax competition.

Since the EU's enlargement in 2004, two opposing forces have shaped the evolution of tax rates. On the one hand, harmonisation mechanisms aimed at limiting aggressive tax planning, particularly through the ATAD directives and the OECD BEPS initiative, have pushed tax systems in a more coordinated direction. On the other hand, many member states, especially the newer economies of Central and Eastern Europe, continue to use corporate taxation as a tool in the competition for international investment. The result is persistent heterogeneity in tax regimes, which may either lead to diverging country-specific developments or to the formation of stable groups of countries with similar tax-policy dynamics.

The central research question of this study is therefore: Do EU member states converge toward a single level of statutory and effective corporate taxation, or do they form separate convergence clubs with their own internal dynamics?

To address this question, two hypotheses are tested:
Null hypothesis (H_0): *There is no single convergence process; countries split into several clubs with distinct long-term trajectories in both statutory and effective tax rates.*
Alternative hypothesis (H_1): *A single convergence trend exists, either in statutory taxation or in ETRs.*

To test these hypotheses, we apply the Phillips–Sul (2007, 2009) methodology, which captures heterogeneous dynamics in panel data without assuming a common steady state. The method is based on the log-t test, which evaluates the existence of a single convergence path, followed by a club-clustering algorithm that endogenously identifies groups of countries with similar long-run trajectories. This approach is well-suited to tax-policy analysis, where countries combine different strategies aimed at competitiveness, fiscal stability and investment support, resulting in highly heterogeneous behaviour.

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The empirical analysis uses a balanced panel of statutory and effective corporate tax rates for 27 EU member states from 2004 to 2023. The first variable is the statutory corporate income tax rate, expressed as a percentage, representing the official legislative rate in each year. The second variable is the effective tax rate (ETR), which captures the real tax burden after considering allowances, depreciation rules, and specific tax regimes. Data on statutory and effective rates come from the European Commission's Eurostat database and the ZEW database. The panel is fully balanced, as all member states are included for the entire period.

This dataset allows us to run the single-convergence log-t test and then apply the club-convergence algorithm separately for both variables. Comparing the results for statutory and effective rates enables the determination of whether the dynamics of actual tax burdens differ from those of declared tax policy and whether effective rates exhibit stronger or weaker tendencies toward convergence.

The methodological framework follows the model developed by Phillips and Sul (2007), which was later expanded to include applications to economic and fiscal data (Phillips & Sul, 2009). The authors assume that any economic variable can be expressed as the product of a common factor, capturing the overall trend, and an individual component reflecting specific deviations of each unit. To capture this heterogeneity, they propose a framework that analyses convergence dynamics without assuming a single target equilibrium. Their model, widely known as the club-convergence approach, is based on decomposing the variable X_{it} into a common component μ_t and an individual factor δ_{it}:

$$X_{it} = \mu_t \, . \, \delta_{it} \tag{1}$$

This equation assumes that all countries share a common trend, μ_t, although each may differ in its individual dynamics, δ_{it}. If the ratio of individual factors between countries moves toward one over time, the system converges to a common trajectory.

For empirical testing, the following relative transition measure is used:

$$h_{it} = \frac{X_{it}}{\frac{1}{N}\sum_{i=1}^{N} X_{it}} \tag{2}$$

where h_{it} expresses the position of a country relative to the sample average, if h_{it} approaches 1, the country moves closer to the average, and if it consistently deviates from 1, it indicates a distinct long-term trend.

The authors then define the variance of these measures as:

$$H_t = \frac{1}{N}\sum_{i=1}^{N}(h_{it} - 1)^2 \tag{3}$$

which expresses the degree of heterogeneity in the system. To test for convergence, the following logarithmic regression is used:

$$\log\left(\frac{H_t}{H_1}\right) - 2\log(\log t) = a + b \, \log t + u_t \tag{4}$$

where the parameter b indicates the direction of the process. If $b > 0$, H_t decreases and the countries converge, and if $b < 0$, the variance increases and the system diverges. The test is interpreted through the t-statistic, which is compared with the one-sided critical values (−1.28, −1.65, −2.33) at the 10%, 5% and 1% significance levels. If the full panel does not show a single convergence path, the Phillips–Sul algorithm allows for endogenous formation of smaller groups of countries, known as convergence clubs. The algorithm proceeds in several steps. First, countries are ranked according to the most recent value of their tax rate. Then, the core of a convergent group is tested and must satisfy the condition $t > -1.65$. Additional countries are added to the core one by one if they pass the test, until the entire panel is exhausted. If some countries remain outside the group, the algorithm is applied to them again. The result is a division of the sample into several stable clusters with homogeneous internal dynamics. Methodologically, this study follows earlier research that documented the existence of club convergence in tax indicators within the EU (Regis et al., 2015). The Phillips–Sul approach makes it possible to distinguish between short-term fluctuations and long-term trends, which provides a more realistic picture of how national fiscal policies adjust to the common economic environment. This method is therefore well suited for testing the hypothesis that tax harmonisation in the European Union does not

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take the form of a single unified process, but rather represents a dynamic equilibrium of several stable groups of countries that share similar tax strategies and institutional frameworks.

4. Results and Discussion

4.1 Overview of Corporate Tax Rates from 2004 to 2023

In the European context, corporate taxation has long been shaped by a combination of economic, political and institutional factors, which generate substantial differences among member states. Corporate tax is neither a stable nor a homogeneous element of national tax systems, since the structure of the tax base influences its level, the macroeconomic situation, public debt levels, collection efficiency, tax reliefs and investment incentives. Differences in both statutory and effective rates, therefore, do not arise in isolation but reflect distinct economic models and fiscal strategies across member states. This results in a persistent segmentation of the EU into several groups of countries with similar tax characteristics (Andrejovská & Hudáková, 2016; Mihoková et al., 2016; Víghová et al., 2024). For this research, a panel of 27 EU member states, covering the period from 2004 to 2023, was used. The variables examined were the statutory corporate tax rate (Figure 1) and the effective tax rate (Figure 2), both expressed as percentages and sourced from Eurostat and ZEW.

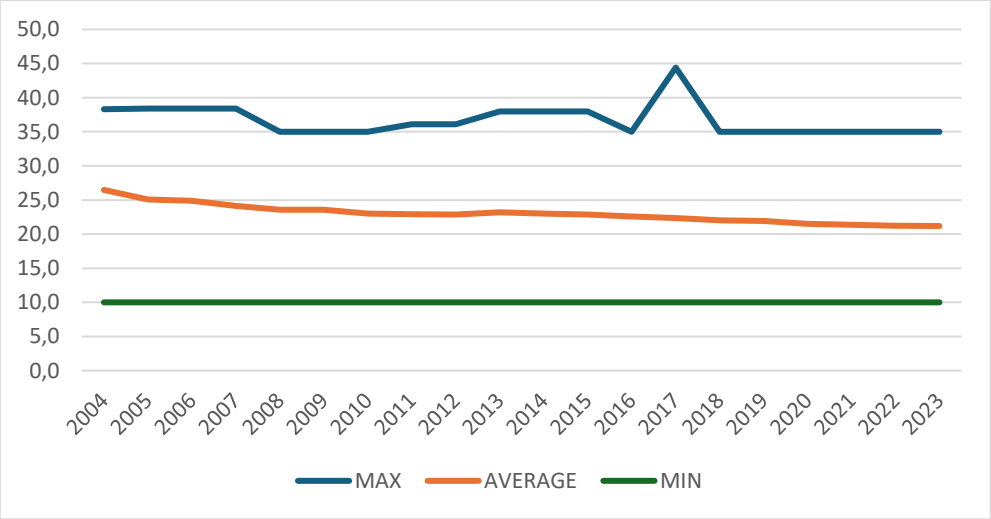


Figure 1. Statutory tax rates in EU countries (2004-2023)
Source: Eurostat (Own processing)

Figure 1 shows that the maximum rates in the EU remain stable over the long term, at around 35 to 38 per cent, with only one fluctuation in 2017. The average rate declines slowly but steadily, reflecting mild downward competitive pressure. The minimum rate remains unchanged throughout the entire period, indicating that real tax competition primarily occurs at the middle of the rate spectrum, rather than at the lower end.

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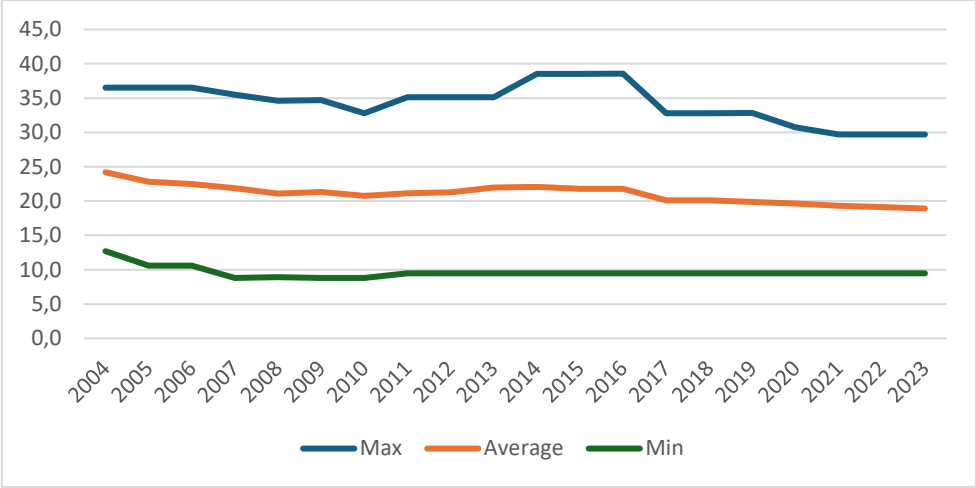


Figure 2. Effective tax rates in EU countries (2004-2023)
Source: Eurostat, ZEW (Own processing)

Figure 2 for effective tax rates shows that the maximum values after 2010 do not follow a clear downward trend, but fluctuate within a band of roughly 34 to 38 per cent, reaching higher levels mainly between 2013 and 2016. The average effective rate has a long-term, although gradual, downward trend, while the minimum values remain virtually unchanged.

4.2 Phillips–Sul Club Convergence

Statutory tax rates
The application of the Phillips–Sul method in this study was used to test whether the development of statutory corporate tax rates in EU member states follows a heterogeneous pattern that a single convergent trend cannot explain. The aim was to determine whether EU countries converge toward a common level of taxation or form separate groups of countries that exhibit similar tax-policy dynamics. The calculations were carried out on a panel dataset covering the period 2004 to 2023, which represents two decades of significant tax-policy changes, from the accession of new EU members, through the post-2008 crisis, to the implementation of ATAD measures and the OECD BEPS initiatives.

The method was applied in several steps. The initial log-t test produced a t-statistic of −8.33. This result shows that the null hypothesis of a single convergence path must be rejected, meaning that EU member states do not share a common convergent trajectory. The next step was to apply the Phillips–Sul club algorithm, which endogenously divided the countries into three stable convergence clubs.

The first club (A) comprises countries with high statutory corporate tax rates, including Malta, Portugal, Germany, France, Greece, and Latvia. These are states whose tax rates have remained above the European average for a long time, and their development is relatively stable. The average rate of this club in the last five years reached 28.3 per cent. The t-statistic for this group was −0.491, indicating no significant internal divergence. A noteworthy finding is the inclusion of Latvia, which, although it does not belong among high-tax countries in absolute terms, was grouped here because its rate dynamics followed a similar path.

The second club (B) is the largest group and includes countries with medium tax rates: Italy, the Netherlands, Belgium, Spain, Luxembourg, Austria, Denmark, Slovakia, Sweden, Estonia, Finland, the Czech Republic, Poland, Slovenia, Croatia, Romania and Lithuania. This club exhibits a slightly declining trend in rates, with its recent average reaching 21.4 per cent. The t-statistic of −1.61 signals weak but statistically significant internal divergence. These countries share a general direction of

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development but with greater variability, reflecting differences in fiscal strategies and responses to economic cycles.

The third club (C) contains four low-tax countries: Cyprus, Ireland, Hungary and Bulgaria. These are typical low-tax economies that use corporate tax as a competitive tool. The average rate in this club was 11.4 per cent, and the t-statistic of 4.43 confirms very strong internal convergence. This is the most homogeneous group, and its dynamics suggest a stable long-term strategy of maintaining low taxation. Overall, the results confirm that tax harmonisation in the European Union has a segmented character. Contrary to theoretical expectations of gradual convergence, member states form several stable groups whose boundaries do not change over time.

The development of average statutory tax rates by clubs is presented in Figure 1. The curves represent the average of each club across the examined period. The graph clearly shows that all groups experienced a slight decline in rates, but the pace and level of this decline differ significantly. Club A maintains rates around 30 per cent over the long term, with only a modest reduction after 2008. Club B shows a gradual decrease, reflecting the long-term trend of fiscal competition in Central Europe. Club C shows the lowest and most stable rates, stabilising below 13 per cent after 2017. The graph, therefore, clearly confirms the vertical segmentation of tax levels in Europe.

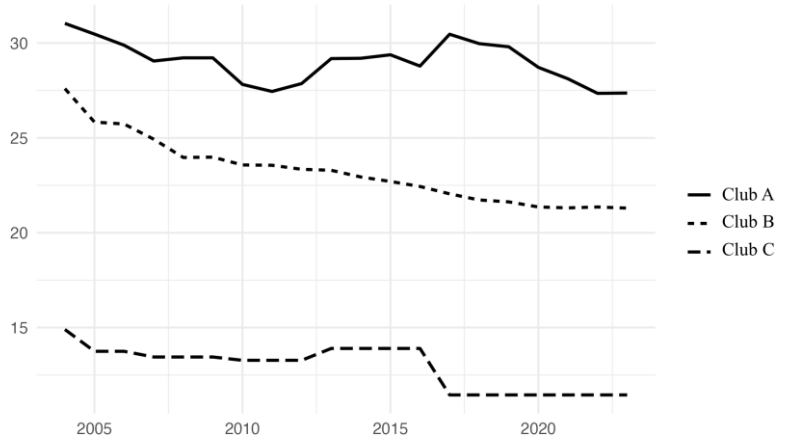


Figure 3. Average statutory tax rates by club (2004 to 2023)
Source: Own processing

Figure 3 clearly shows that Club A, the high-rate group, remains close to 28 per cent, Club B declines from 25 per cent to 21 per cent, and Club C stays consistently below 12 per cent.

Figure 4 shows the development of individual transition paths hit for each country within the clubs. These curves capture the relative position of each country compared with its club average and therefore reflect the dynamics of convergence. The value hit = 1 represents the club average. Countries in Club A fluctuate around this value, which confirms their relative stability. Club B shows larger fluctuations, indicating a transitional adjustment period between older and newer member states. In Club C the country trajectories are very close to each other and remain below 1 over the long term, which corresponds to their low rates and homogeneous development.

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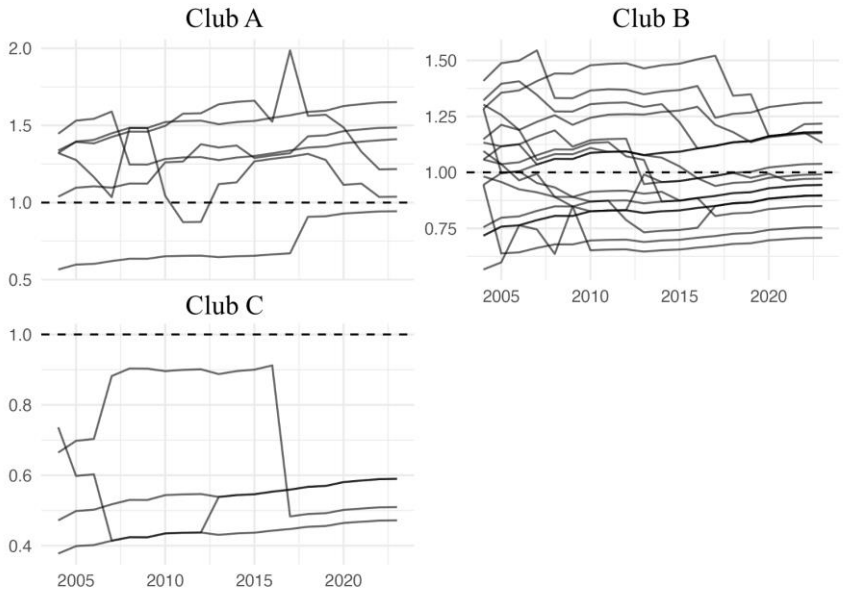


Figure 4. Transition curves by club (statutory rates)
Source: Own processing

Curves of individual countries within the clubs converge toward the value 1, which indicates within club convergence. Figure 5 summarises the average transitional curves for the three clubs. The value 1 represents the EU average. The curve of Club A moves above the level 1, which means that the countries in this group have long term higher tax rates than the union average. The curve of Club B is close to 1, which confirms that this is the core club that represents the overall European trend most accurately. The curve of Club C is consistently below 1 and approaches the value 0.6, which corresponds to low rates and a stable tax policy of these countries.

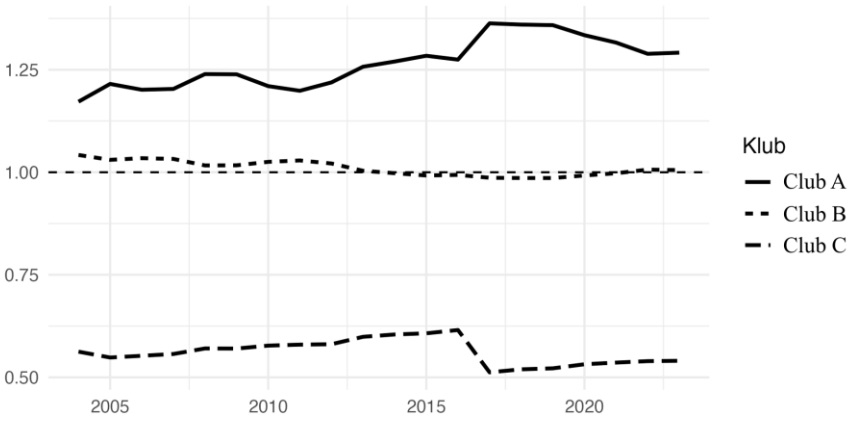


Figure 5. Average relative transition measures by club (statutory rates)
Source: Own processing

The curves for clubs A, B and C fluctuate around the equilibrium value of 1. Club A stays above 1, reflecting high rates, Club B remains close to 1, the middle group, and Club C stays consistently below 1, reflecting low rates.

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These results have a clear economic interpretation. Club A represents countries that prioritise fiscal stability and higher levels of public revenue, which limits the scope for aggressive tax competition. Club B is a mix of older and newer member states where a long-term process of adjustment and harmonisation is taking place. Club C represents competitive economies that have maintained low rates over the long run and show strong internal stability. From a dynamic perspective, the internal convergence processes within each club have stabilised. This shift coincides with the introduction of the ATAD and BEPS measures, which reduced the intensity of tax competition among countries. At the same time, the persistent differences between clubs form long-lasting equilibria that reflect the structural diversity of European tax systems.

Overall, the results confirm the theoretical assumptions of Phillips and Sul (2007, 2009) that in a heterogeneous economic environment, a single convergence path does not emerge, and instead multiple equilibrium states develop. The European Union therefore represents a space where fiscal harmonisation does not imply uniformity, but the long-term coexistence of several stable tax-policy regimes. These findings are consistent with the empirical work of Regis et al. (2015), who identified several convergence clubs in corporate taxation. The results can therefore be understood as evidence that tax harmonisation in the EU does not occur through full convergence but through the formation of stable clusters or convergence clubs that reflect historical, economic and institutional differences among member states.

The overall log-t test for the full panel of 27 countries produced a value of $t = -8.33$, which means that single-path convergence is rejected. The algorithm identified three stable clubs.

Club A represents a high-tax model, countries with traditionally strong fiscal systems. Club B includes most countries, which gradually reduce rates but do not reach full homogeneity. Club C forms the low-tax core of the EU, where countries converge very quickly.

A comparison with the study by Regis et al. (2015) confirms the three-club structure, although in this analysis Club C shows higher stability. Delgado and Presno (2017) and Delgado et al. (2019) also report a polarisation within the EU, which aligns with these findings.

From a long-term perspective, the EU is not diverging but instead segmenting into stable clubs that reflect structural differences in economic policy.

Table 2. Allocation of the countries across the clubs (statutory rate)

Club	Countries	Average rate	t-statistics
A	France, Germany, Greece, Latvia, Malta, Portugal	28.3%	-0.491
B	Austria, Belgium, Croatia, Czechia, Denmark, Estonia, Finland, Italy, Lithuania, Luxembourg, Netherlands, Poland, Romania, Slovakia, Slovenia, Spain, Sweden	21.4%	-1.61
C	Bulgaria, Cyprus, Hungary, Ireland	11.4%	+4.43

Source: Own processing

The results clearly show that the process of tax harmonisation in the European Union does not follow a single convergence path but instead leads to a segmented clustering of countries into smaller, internally stable convergence clubs. The overall log-t test reached a value of -8.33, which means that the null hypothesis of a unified convergence process is rejected. The development of statutory corporate tax rates in the EU therefore cannot be described by a single common trajectory.

The strongest internal convergence is found in the low-tax club (C), which includes Cyprus, Ireland, Hungary and Bulgaria. These countries form a distinct group with a stable tax policy and long-term low

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rates averaging around 11 percent. This result confirms the existence of EU economies whose growth model is built on the competitive advantage of low capital taxation. The t-statistic of 4.43 for this club reflects strong internal homogeneity and a clear long-term direction without any sign of divergence.
The medium-rate club (B) represents the core of the EU and includes most of the older and newer member states. Rates in this group range between 20 and 25 percent and gradually decline, which reflects adaptation to global trends and the need to maintain competitiveness. The t-statistic of −1.61 suggests only weak internal convergence, which is the result of differences in fiscal discipline, economic structures and political preferences across governments.

The high-tax club (A), including countries such as Germany, France and Portugal, is characterised by consistently high rates around 28 to 30 per cent. Although there was a slight decline after 2008, these countries maintain fiscal models oriented toward stable public revenues. The t-statistic of −0.491 indicates that the group does not diverge but maintains a long-term equilibrium at a high level of taxation.

The average rate shown in Table 2 represents the average statutory rate after the major period of tax reforms. A full-period average would mix historical and current values, making it unsuitable for interpreting convergence clubs; therefore, a five-year average is used for clearer comparison.

The graphical results support these findings. The development of average rates across clubs shows clearly separated trajectories, with a stable vertical distance between them. The transition curves demonstrate that countries within each club fluctuate around their stable equilibrium, while the EU average remains roughly midway between high- and low-tax regimes. Compared with previous research (Regis et al., 2015), the findings of this study are entirely consistent. Like those studies, this analysis confirms the existence of several stable clubs whose boundaries remain essentially unchanged over time. European tax policy, therefore, does not evolve toward complete harmonisation but toward the long-term coexistence of different fiscal regimes. The discussion suggests that European fiscal integration is a balance between harmonisation and sovereignty. Convergence appears only within clubs, not across the EU. This means that tax policy remains one of the last areas where strong national diversity persists. Despite long-standing efforts toward harmonisation, the evidence shows that the European Union functions as a space of multiple fiscal equilibria, ranging from stable high-tax regimes to competitive low-tax economies. This conclusion supports the theoretical assumptions of Phillips and Sul (2007, 2009) that in a heterogeneous environment, a unified convergence path is unlikely, and the natural outcome is the formation of stable clubs with their own adjustment dynamics.

Effective tax rates
In the second part of the analysis, the Phillips–Sul method was applied to effective tax rates (ETR), which more accurately reflect the real level of corporate taxation than statutory rates alone. The goal was to determine whether EU member states move toward a common level of effective taxation, or whether ETR also form separate, long-term stable groups of countries with different tax-policy dynamics. The analysis covers the period 2004 to 2023, a timeframe marked by major shifts in corporate taxation, including the financial crisis, EU enlargement, reform waves in Eastern Europe, and the introduction of the OECD BEPS initiative and the EU's ATAD legislation.

The first step was the overall log-t test for the entire panel. The resulting t-statistic reached −8.29, indicating that the hypothesis of a single convergence path must be rejected, just like in the case of statutory rates, effective tax rates do not converge toward one common level. Instead, within the European Union, there are distinct long-term ETR trajectories shaped by countries' fiscal preferences, the extent and structure of tax reliefs, and the overall competitiveness of their tax systems. The next step was to apply the Phillips–Sul club algorithm, which endogenously identified two stable convergence clubs. This is a noticeably different outcome from statutory rates, where three clubs emerged. The difference confirms that effective rates behave differently from statutory ones, and that countries with

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similar statutory rates may face very different effective tax burdens due to reliefs, loopholes or specific tax regimes.

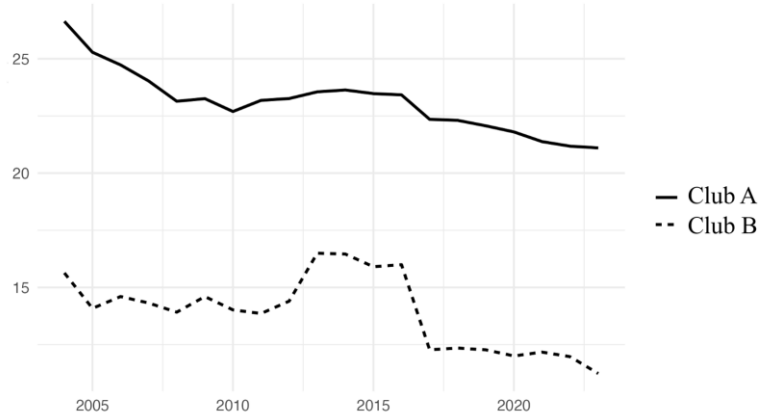


Figure 6. Average effective tax rates by club (2004 to 2023)
Source: Own processing

Club A, the main European convergence block

The first and largest club comprises most EU member states, including Germany, France, Spain, Austria, Slovakia, the Czech Republic, Slovenia, and Estonia. It represents the central European block with effective taxation stabilised roughly around 20 to 22 per cent. The average ETR over the last five years reached 21.5 per cent. The t-statistic for this club was −1.18, indicating weaker but still acceptable convergence, while also suggesting higher heterogeneity within the group. Several countries oscillate around the average level, and their transition curves show gradual adjustment toward a shared trajectory. The internal variability reflects differences in approaches to tax reliefs, investment incentives and the structure of national corporate sectors. The development of the average ETR for this club shows a gradual decline from 2000 until the period after 2020, with rates remaining consistently above the European average (Figure 6).

Club B, low-tax ETR economies with strong internal stability

The second club consists of the countries with the lowest effective tax burdens in the EU: Ireland, Lithuania, Poland, Cyprus, Hungary and Bulgaria. These economies systematically use tax policy as a competitive advantage and maintain long-term low taxation of corporate activity. The average effective rate in this group reached 11.9 per cent, roughly half of the level observed in Club A. The t-statistic of 0.604 confirms clear internal convergence within this group. The relative transition curves lie well below the value of 1 but remain tightly clustered, which highlights the homogeneous nature of this tax regime. The graph of ETR development by clubs shows that this group maintains low effective rates without major deviations or cyclical fluctuations. The sharp jump in the transition curve of Club B around 2015 is caused by Cyprus, whose ETR briefly surged from about 16 per cent to 28 per cent before falling back again, creating an extreme deviation from the average (Figure 6).

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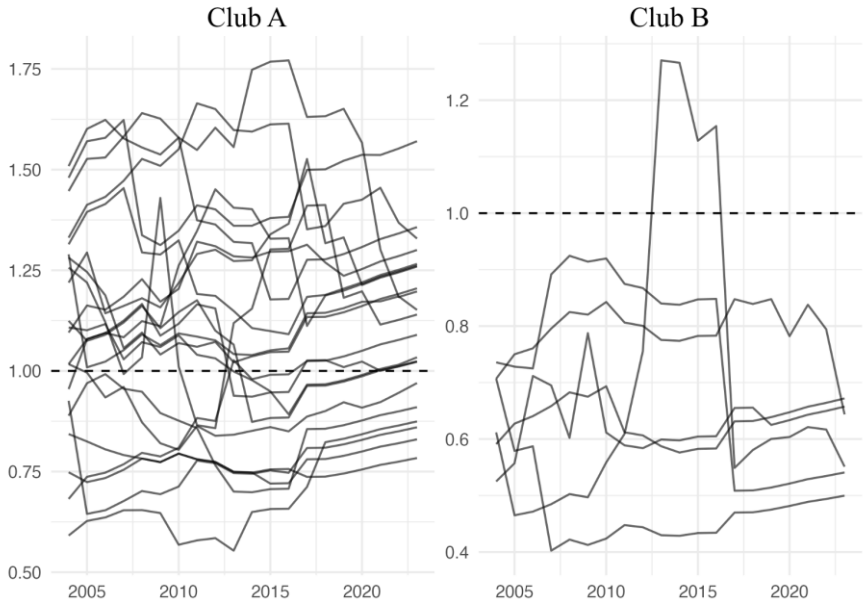


Figure 7. Transition curves by club (ETR)
Source: Own processing

The individual transition curves for countries within each club illustrate how their relative positions evolve in comparison to the European Union average. The value h = 1 represents the EU average. For Club A, the curves typically fluctuate around the level of 1, with a slight upward trend after 2015, indicating a gradual increase in effective rates relative to the overall EU average. In contrast, the countries in Club B remain consistently below the value of 1, which corresponds to their low ETR levels and their long-term strategy of attracting investment through tax incentives.

The average transition curves of the individual clubs display clear vertical separation (Figure 7). Club A stays above the value of 1 over the long term, while Club B remains below 1. These differences are stable, resistant to economic shocks and reflect the structural configuration of the tax systems in each country.

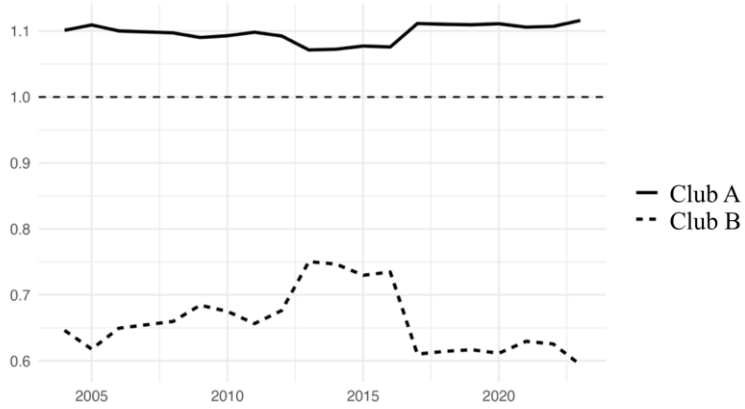


Figure 8. Average relative transition measures by club
Source: Own processing

Figure 8 shows the average relative transition measures for effective tax rates (ETR) in the two convergence clubs identified using the Phillips–Sul method. The value h = 1 represents the EU average, so the curves illustrate how each club evolves relative to the overall European trend.

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Club A, which comprises most EU member states, consistently remains above the value of 1. This means that its members have experienced higher effective taxation than the EU average in the long term, and their trajectory is relatively stable, without major shocks. In contrast, Club B, consisting of low-tax countries, lies clearly below the value of 1, which confirms its low ETR levels and its stable long-term model based on tax competition. The slight decline after 2016 indicates a widening gap between the low-tax club and the rest of the EU. Figure 8, therefore, visually confirms that effective tax rates do not converge toward a single level but remain separated into two distinct, stable tax equilibria.

The overall log-t test for the panel of 27 countries yielded a value of t = −8.29, indicating that the hypothesis of a single convergence path must be rejected. This indicates that EU member states do not follow a single common trajectory in terms of effective tax rates, but instead exhibit diverse long-term taxation patterns that reflect structural differences in their tax systems, the scope of tax reliefs, and the broader fiscal strategies of national governments.

The club algorithm identified two stable convergence clubs (Table 3). Compared with statutory rates, where three clubs emerged, the two-club structure for ETR reflects the fact that effective rates capture the real tax burden of corporate activity more accurately and depend less on the formal level of the statutory rate. As a result, countries do not form a middle group, but rather split into two clearly distinguishable clusters with distinct dynamics.

Table 3. Allocation of the countries across the clubs (effective rate)

Club	Countries	Average rate	t-statistics
A	Germany, Spain, Malta, Luxembourg, Italy, Portugal, Belgium, Netherlands, France, Austria, Greece, Slovakia, Denmark, Finland, Sweden, Czechia, Slovenia, Latvia, Romania, Estonia, Croatia	21.5 %	-1.179
B	Ireland, Lithuania, Poland, Cyprus, Hungary, Bulgaria	11.9 %	0.604

Source: Own processing

The first club represents the majority of EU member states and can be described as the main European bloc. It includes countries with standard tax systems and medium levels of taxation, whose effective rates have remained around 20 to 22 per cent over the long term. The average ETR over the last five years reached 21.5 per cent. The t-statistic of −1.18 indicates weak but still acceptable internal convergence, while also suggesting mild heterogeneity driven by differences in the tax base, available reliefs, and investment incentives. The transition curves indicate that most countries gradually converge toward a shared trajectory and do not exhibit signs of divergence in the long term. The development of the average ETR confirms a slow but steady decline in rates from 2004 to the present.

The second club comprises countries with the lowest effective taxation: Ireland, Lithuania, Poland, Cyprus, Hungary, and Bulgaria. These economies systematically utilise tax policy as a competitive advantage and maintain low overall corporate tax rates. The average ETR in this group reached 11.9 per cent, roughly half the level of the first club. The t-statistic of 0.604 confirms clear internal convergence and high homogeneity within the group. The transition curves remain consistently below the value of 1 and lie close together, signalling a consistent and sustainable low-tax regime. The development of average rates shows that these countries not only maintain low ETR levels but also display minimal fluctuations.

The graphical results support these findings. The average rates by club are clearly separated and a stable vertical distance exists between the two groups. The transition curves show that both clubs move toward their internal equilibria and do not display any tendency to merge or overlap over time. The EU average remains between the two groups, which illustrates that the EU does not form a unified tax level but rather occupies a space between two stable poles.

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A comparison with previous studies confirms that these results align with the literature describing the European tax landscape as heterogeneous and segmented. As with statutory rates, the effective rates show that the EU is moving toward a stable coexistence of different fiscal regimes rather than full harmonisation. Effective rates, however, more clearly reveal only two stable equilibria, which reflect differences in the real tax burden caused by deductions, special regimes and the varying economic structures of member states.

The discussion indicates that fiscal integration in the EU is a balance between harmonisation efforts and national preferences. Convergence appears only within the clubs, not across the entire Union. Tax policy therefore remains an area with substantial national autonomy. Effective rates confirm the assumptions of Phillips and Sul that in a heterogeneous economic environment, multiple stable convergence clubs with their own adjustment dynamics are the natural outcome.

Conclusions

The analysis of the development of statutory corporate income tax rates in EU member states between 2004 and 2023 shows that the process of fiscal convergence is fragmented. Instead of following a single trend, countries group into three stable convergence clubs with distinct tax philosophies and long-term dynamics. This result confirms that complete tax harmonisation within the EU is unlikely, since member states pursue different strategic objectives: some prioritise fiscal stability and higher public revenues, while others build competitiveness through low rates.

The analysis of effective tax rates (ETR) provides a clearer picture of the segmentation of tax regimes within the EU. In this case, only two clubs were identified, which indicates that when it comes to the actual tax burden on corporate activity, countries split even more clearly into two strategically different groups. The first group represents the EU core with a stabilised effective tax level of around 20 to 22 per cent, while the second consists of low-tax economies that maintain long-term ETR levels of roughly 12 per cent. The differences between the clubs are stable over time and there is no dynamic suggesting convergence. The fact that effective rates reveal only two stable equilibria highlights the importance of reliefs, deductions and special regimes, which create very different real tax burdens even when statutory rates are similar.

From a policy perspective, the recommendation is to strengthen coordination rather than unify tax systems. The European Commission should support mechanisms that limit harmful tax competition while respecting the heterogeneity of member states' economic structures. A suitable direction includes further development of instruments such as the Common Consolidated Corporate Tax Base (CCCTB), increased transparency of tax regimes and the harmonisation of anti-avoidance rules, since ETR differences are most visible in these areas.

From a scientific view, the research confirms the suitability of the Phillips–Sul method for analysing heterogeneous fiscal processes. Its application to statutory and effective rates shows that convergence mechanisms differ depending on whether the formal rate or the real tax burden is examined. Future research could be extended to dividend taxation, sector-specific differences, disparities between large and small firms or regional variation within member states. Such extensions would help assess whether tax competition is shifting from rate levels toward the tax base, reliefs and optimisation schemes.

Based on the results, the research question can be answered clearly: EU countries do not converge toward a single level of statutory or effective taxation but instead form separate convergence clubs over the long term. The global log-t test for both types of rates yielded strongly negative values, confirming the rejection of a unified convergence trend and the existence of multiple stable tax regimes. The null hypothesis, which states that countries do not follow a single common trajectory but create several clubs with different dynamics in statutory and effective tax rates, is therefore supported. In contrast, the alternative hypothesis of a single convergence path is rejected.

Overall, the European tax landscape is evolving into a stable, multi-layered equilibrium of fiscal regimes. Instead of converging toward a single level, countries form long-term clubs that reflect their economic models, political preferences and historical development. The results highlight that fiscal harmonisation in the EU is a process of coordination rather than complete unification and that differences between member states remain a lasting part of its economic reality.

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THE PROVISION OF SECURITY IN THE EU: AN INTERDISCIPLINARY ANALYSIS OF SECURITY AS A PUBLIC GOOD IN THE ERA OF TRANSNATIONAL THREATS

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Abstract. This paper examines security as a public good within the context of its provision at the European Union level, analysing its theoretical, economic, and institutional dimensions. It is grounded in the concept of non-excludability and non-rivalry of public goods and demonstrates that modern security threats—ranging from hybrid threats, terrorism, organised crime, and pandemics, to cyber-attacks—transcend national state borders, thereby undermining traditional state-centric models of security provision. The author employs an interdisciplinary research approach, combining analytical methods from economics, political science, European studies, and security studies, which allows for a comprehensive capture of the multi-level nature of security provision as a public good. The analysis highlights that the EU is gradually assuming the role of a security provider through common policies, mechanisms, and instruments, while identifying fundamental obstacles, particularly in the form of fragmented competences, uneven Member State contributions, and inadequate financing. Empirical examples, such as the joint responses to the COVID-19 pandemic and the Russian aggression against Ukraine, confirm the growing necessity for coordinated, collective solutions. The article concludes that, given the deterioration of the regional and global security environment and the deepening of instability and uncertainty, the strengthening of European cooperation, solidarity, and financing is essential for the sustainable provision of security as one of the key European public goods.

Keywords: Security as a public good; European Union; collective security; fragmentation of competences; strategic autonomy; solidarity; political and institutional challenges

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1. Introduction

Security stands among the fundamental values and, simultaneously, the core preconditions for the existence of modern democratic societies worldwide (Palárik et al., 2018; Kavan, 2021; Wadjdi et al., 2023; Belan, 2023; Bamigboye, 2023; Szabó, 2023). It is not merely a negative state defined by the absence of threats or risks, but also a positive prerequisite for the development of liberty, prosperity, and sustainable development. The European integration process was, from its very inception, founded upon the idea that peace and stability are indispensable for economic growth and social cohesion (Androniceanu et al., 2021; Razminienė & Tvaronavičienė, 2024). Today, it is increasingly evident that security is not only a political and social value but

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also a public good, the provision of which is of critical importance to all citizens of the European Union (EU). This perspective—security as a public good—allows for the question of its assurance (provision) to be conceptually grasped not only in a national but also in a European and global context (Baldwin, 1997; Engerer, 2011; Ivančík, 2012).

The concept of public goods is closely linked to classical economic theory, which characterises them as goods that are non-excludable from consumption and non-rivalrous in use, meaning they cannot be supplied solely to selected individuals but pertain to society as a whole (Samuelson, Nordhaus, 2009; Atkinson, Stiglitz, 2015). Security meets these criteria across multiple dimensions: an individual cannot be excluded from the benefits deriving from a stable and secure environment, and its consumption by one individual does not diminish the level of security available to others (de Vries et al., 2022). Security represents a specific type of public good primarily challenged by issues such as underproduction, tendencies towards free-riding, and financing concerns (Ivančík, 2012). Within the framework of the European Union, security therefore becomes an ideal case for considering the joint production and distribution of this good (Engerer, 2011). European societies face multiple serious security challenges in the 21st century that are closely related to deepening globalisation, increasing international interconnectedness, and significant shifts in the regional and global security environment (Majchút, 2018; Burinskas & Tvaronavičienė, 2022; Ybáñez, 2022). Hybrid threats, cyber-attacks, terrorism, and organised crime disregard the borders of individual states and possess a transnational character. Russia's military aggression against Ukraine since 2022 has revealed not only geopolitical but also economic and energy vulnerabilities in Europe. Furthermore, the war has exposed that the security of Europe is existentially intertwined with collective responses and that individual EU Member States do not independently possess sufficient capabilities and capacities to guarantee stability and protect their own populations (Jurčák & Ivančík; 2023; Hajiyeva, 2024; Ivančík, Andrassy, 2025, Frederick et al., 2025).

In addition to traditional threats, the significance of new factors is increasing, such as escalating great-power rivalry between the United States and China, which has significant implications for European security and its efforts towards strategic autonomy. Internal security is thus inseparably linked with external security, compelling the EU to review and reassess its institutional frameworks and capacities.

It is precisely for this reason that it is meaningful to examine security as a European public good. As the theory of public goods demonstrates, there are domains where it is more efficient and equitable to assure goods at a supranational level than at the level of individual nation-states. Bossong and Rhinard (2012) emphasise that EU internal security exhibits the characteristics of a typical public good: its benefits are collective, its insufficient provision creates risks for all, and its effective realisation necessitates coordination among states. In this regard, the coronavirus disease (COVID-19) pandemic represented a watershed moment, where the joint procurement of vaccines confirmed the practical utility of the European public good concept (Anev Janse et al., 2025). Similarly, the areas of energy security and defence policies also indicate that common European solutions can be more effective than isolated national approaches.

The examination of security as a public good inevitably requires an interdisciplinary approach. The traditional understanding of security was long anchored in a state-centric framework, in which the nation-state served as the primary guarantor of security. However, developments in recent decades have shown this model to be insufficient. Academic research into security, therefore, combines insights from economics, which offers the categories of public goods and the concept of collective action, with political science and European studies, which analyse the dynamics of inter-state cooperation and the European integration process. Security studies also form an integral part of the analytical framework, drawing attention to the dynamically changing nature of security threats and challenges and the necessity for a comprehensive, multi-level approach. This interdisciplinary framework allows for a better understanding of why security within the European environment must be examined not as a set of isolated national strategies, but as a joint project of public interest.

From a methodological perspective, the paper employs a combination of several approaches. Firstly, it relies on a content analysis of available scholarly texts and strategic documents of the European Union that address the issue of security as a public good. The second element is a theoretical analysis of the public goods concept in both classical and modern economics, applied to the specific domain of security. The third methodological pillar

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is critical analysis, which allows for reflection on the limitations of existing research and highlights potential contradictions between theory and practice. Furthermore, institutional analysis is applied, tracing the evolution and functioning of specific EU policies, such as the ProtectEU strategy, the common policy on the internal market and security, and instruments aimed at cyber security and civil protection.

These approaches are complementary and provide a comprehensive picture of security as a European public good. The content and theoretical analysis enable the research to be anchored in academic discourse, while the institutional and comparative analysis reveal the practical mechanisms through which the European Union overcomes the limitations of purely national security assurance. Finally, the critical perspective is essential to realistically assess the extent to which declared goals and common European commitments translate into real-world implementation and the capacity to collectively protect European citizens.

2. Security as a Public Good: Theoretical and Economic Foundations

The discussion regarding security as a public good follows a long tradition within economic theory that distinguishes between private and public goods. Samuelson and Nordhaus (2009) defined public goods as those characterised by two core properties: non-excludability from consumption and non-rivalry in use. Non-excludability signifies that once a specific public good is provided, no individual can be effectively prevented from utilising its benefits. Non-rivalry denotes a situation where the consumption of the good by one individual does not diminish the quantity of the good available to others. Classic examples of public goods include clean air, street lighting, and national defence (Ivančík, 2012; Mikušová Meričková & Stejskal, 2014).

Within this framework, security appears to be a model case of a public good. Insofar as protection against external aggression or internal threat is assured, the entire society profits from this state. A citizen cannot simply be excluded from the benefits of the security environment, just as their sense of security does not diminish the level of security available to others. Engerer (2011) emphasises that security possesses an additional, specific characteristic: it is not only the absence of risk or threat, but also a positive state of certainty and confidence in the stability of the social and political environment. This aspect differentiates security from other public goods, which are mostly purely material or technical in nature.

The distinction between national, European, and global security is crucial when applying the public goods concept. In the traditional understanding, security was primarily a national public good, assured by the state through the military, police, other armed security forces, and judicial institutions. However, globalisation and technological advancement have caused threats to increasingly assume a transnational character. Cyber-attacks, terrorism, organised crime, hybrid, and environmental threats cannot be isolated within the borders of a single state. Therefore, the concept of security as a regional and global public good is being increasingly applied (Bossong & Rhinard, 2012). The European Union, as a specific integration project, is moving to the forefront in the search for institutional solutions for the provision of this type of good.

Economic theory demonstrates that public goods are systematically threatened by the phenomenon of underproduction. Public goods are often produced in smaller quantities than would be optimal for society because private producers lack sufficient incentives for their output. Since individuals cannot be excluded from their consumption, private providers lack the motivation to invest in their financing to an adequate extent. This problem is known as the free rider dilemma, where actors expect the public good to be provided by someone else, while they themselves profit from it without their own contribution (Mikušová Meričková et al., 2024). In the case of security, this problem manifests at multiple levels. Domestically, individuals may expect the state to guarantee security, while at the international level, small EU Member States often rely on the initiatives and resources of others, especially large states, while contributing less themselves to the assurance of collective security.

The financing of security is therefore a critical issue. Engerer (2011) posits that the optimal level of security provision is not achieved in practice because, unlike private goods, the price mechanism cannot be utilised to express individual preferences and willingness to pay. In the context of the EU, this disproportion is exacerbated by the fact that the Union's budget amounts to only approximately one per cent of the member states' Gross

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Domestic Product (GDP), while security and defence expenditure remains predominantly the competence of national governments (Anev Janse et al., 2025). This model results in resource fragmentation and the duplication of national initiatives, thereby diminishing the overall efficiency and effectiveness of the system.

Security also entails significant externalities, or spillover effects, that extend beyond the scope of a single state or individual. Positive externalities arise when the enhanced security of one state benefits its neighbours. For instance, the adoption of effective and efficient counterterrorism or organised crime measures within one EU member state contributes to higher security levels across the other member states. Negative externalities emerge when security policy failures in one member state increase risks for the rest of the Union. An example of this is inadequate border protection mechanisms in certain member countries, which can compromise the internal security of the entire European Union.

The public goods problem in the security domain is thus intrinsically linked to the collective action dilemma. As Mancur Olson (2009) highlighted, rational actors tend to minimise their contributions and maximise the benefits derived from the collective endeavour. At the EU level, this dynamic manifests in disputes over the distribution of financial and political costs associated with common security projects. Bossong and Rhinard (2012) argue that this dilemma is particularly evident in internal security initiatives, where certain member states adopt an approach of selective integration or negotiate opt-outs.

From a theoretical perspective, it is therefore imperative that institutional mechanisms are created at the European level to mitigate the free-rider problem and ensure a more equitable distribution of costs and benefits. Such mechanisms may take the form of joint financing, legally binding commitments, or coordinated strategies that reinforce the incentive for member states to contribute to the collective effort. Failure to implement these measures risks security remaining an undersupplied public good, with repercussions for the stability, prosperity, and credibility of the EU as a whole.

Security has long been perceived as a national public good, guaranteed by the state through its monopoly on the legitimate use of force. In the traditional conception, this meant that each state bore primary responsibility for protecting its citizens from both external and internal threats. This model was characteristic of the Westphalian system and dominated particularly throughout the 19th and 20th centuries. The challenge it faces, however, lies in the fact that modern threats transcend national boundaries and can no longer be effectively managed by isolated national policies. Cyber-attacks are a typical example, which may originate in one country but whose consequences affect other countries or even entire regions. Similarly, organised crime, terrorism, and irregular migration are inherently transnational and necessitate a coordinated response.

Consequently, security is increasingly referred to as a European public good. In this conceptualisation, security is provided not merely by individual states, but primarily through common European institutions and policies. The European Union has a dual role in this area: firstly, it strengthens the competences and capabilities of the member states through legal and institutional mechanisms (e.g., Europol, Frontex, civil protection and crisis management mechanisms), and secondly, it creates a framework for the collective resolution of common threats. Bossong and Rhinard (2012) emphasise that in the EU context, security must be understood as the outcome of a collective contribution from all member states, where each member state provides a portion of resources, information, and capacities to create a transnational security space. This approach enables the overcoming of the unequal burden-sharing problem and establishes a legitimate framework for joint measures.

Security also acquires the dimension of a global public good. In a globalised world, it is evident that stability and security in Europe are intrinsically linked to developments in other parts of the world. Climate change, the proliferation of weapons of mass destruction, international terrorism, or geopolitical conflicts generate threats that cannot be isolated within the borders of the continent. Engerer (2011) warns in this regard that security, as a global public good, is even more challenging to provide because there is no supranational authority with sufficient competences and capabilities to guarantee it. In this context, the European Union is compelled to act as one of the key global security actors and contribute to international regimes, alliances, and partnerships that strengthen stability not only in Europe, but also in its neighbourhood and at the global level.

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The distinction between the national, European, and global levels of security provision is therefore crucial for understanding the challenges facing the European Union. While member states strive to maintain their sovereignty in the security sphere, reality increasingly compels them to shift competences to the European level. And although the European level can manage many threats more effectively, it still encounters limits that require coordination and cooperation with partners at the global level.

From a theoretical and economic standpoint, it can thus be concluded that security is a paradigmatic example of a public good that manifests across multiple levels. This multilayered character raises the question of the extent to which the European Union is capable of assuming the role of the provider of this good and how successfully it executes this in practice. The answer to this question necessitates an examination of the concept of European public goods, the historical development of security integration, and the practical policies adopted by the EU. This logically opens the door for the next chapter, which will focus on the European Union and the concept of public goods in the security domain.

3. The European Union and the Concept of Public Goods in the Security Domain

The historical development of the European integration process demonstrates that security was long considered an exclusively national competence, intrinsically linked to state sovereignty. The Westphalian model of international relations enshrined the principle that every state possesses absolute authority to guarantee internal order and defence against external threats. Integration in post-Second World War Europe was thus initially oriented towards economic and financial matters—the establishment of the European Coal and Steel Community (1951) and the European Economic Community (1957) was motivated by the conviction that deepening economic and monetary cooperation would ensure peace and stability. Defence initiatives, such as the plan for a European Defence Community (1952), failed precisely due to concerns over the curtailment of national sovereignty in security and defence issues.

Over time, however, the purely national understanding of security proved to be increasingly ineffective. The rapid rise of cross-border organised crime, the issue of increasing migration, environmental catastrophes, and terrorist attacks in the 1970s and 1980s demonstrated that member states were unable to tackle many threats in isolation. The response was a gradual shift towards common policies in internal security, formally solidified in the 1990s with the adoption of the Maastricht Treaty (1992). This Treaty established the so-called three-pillar structure, within which cooperation in Justice and Home Affairs became an integral part of the European project.

A further significant step was the Amsterdam Treaty (1997), which placed a new emphasis on the Area of Freedom, Security and Justice (AFSJ) and allowed for the progressive transfer of competences into the supranational framework. A fundamental turning point, however, was marked by the terrorist attacks of 11 September 2001 and the subsequent attacks in Madrid (2004) and London (2005). These events accelerated the creation of pan-European mechanisms in the fight against terrorism, strengthened Europol, and encouraged the adoption of several framework decisions that harmonised member states' criminal law in key areas. The Lisbon Treaty (2009) abolished the pillar structure and fully incorporated internal security into the EU's legal and political framework, thereby confirming that security could no longer be understood as an exclusive national competence (Koutrakos, 2012).

The developments at the external level also played a significant role in this process. The EU enlargement to include new member states in 2004 fundamentally shifted the Union's geographical boundaries and necessitated a more coordinated protection of external borders. Simultaneously, the growing interconnection between internal and external security demonstrated that threats cannot be strictly separated. Conflicts in the EU's neighbourhood, such as the war in the former Yugoslavia, the crisis in Libya, or the fighting in Ukraine after 2014 and the outbreak of the full-scale war in 2022, showed that destabilisation in the immediate vicinity has a direct impact on EU internal security (Kompan & Hrnčiar, 2021; Ivančík, Andrassy, 2025; Genini, 2025). This trajectory progressively legitimized the building of the European security apparatus, from Frontex to civil protection and cybersecurity defence mechanisms.

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From a historical perspective, it is thus evident that the EU has gradually evolved from a project of economic and financial integration to an increasingly strong security provider, with security now understood as a European public good. This shift is the result of a long-term process, in which it became clear that the collective guarantee of security is more effective, efficient, equitable, and legitimate than fragmented national approaches.

The concept of European public goods has gained a stronger footing in both academic and political discourse in recent years. Fuest and Pisani-Ferry (2019) point out that there are areas where the provision of public goods at the member state level is not efficient, and where the European Union has a unique capacity to ensure collective benefit. In addition to climate policy, financial stability, and innovation, these areas include security. Ensuring security in an environment of open borders and strong international interconnectedness is a classic example where the European level is better equipped than isolated national solutions.

The EU, however, does not function as a classical state, but rather as a hybrid provider of public goods, combining elements of intergovernmental cooperation with supranational competences (Balfour et al., 2024). This hybridity is exceptionally visible in the security domain. On the one hand, member states remain the main guarantors of internal order and external defence; on the other hand, they are increasingly transferring their powers to the European level through agencies, common funds, and legally binding standards. Anev Janse et al. (2025) emphasise that this model creates a unique type of European public good: security is provided in a combined manner, through the solidarity of member states, joint financial mechanisms, and regulatory frameworks that mitigate the risk of fragmentation.

The significance of the EU as a public goods provider has intensified particularly since 2020. The COVID-19 pandemic revealed that in crisis situations, the Union is capable of coordinating joint solutions that would be inefficient or impossible for individual states to pursue alone. The joint procurement of vaccines, the creation of strategic reserves of medical supplies, and the coordination of cross-border measures were examples of the EU acting as a guarantor of collective security. This experience confirmed that security in the broadest sense—from health to internal and cybersecurity—is becoming a European public good that can only be provided effectively through collective efforts.

Following the above, it is important to stress that the EU is not merely a passive coordinator but actively creates new policies and institutions that enhance its capacity to provide public goods in the security area. Initiatives such as PESCO (Permanent Structured Cooperation), the EDF (European Defence Fund), and mechanisms focused on cybersecurity represent steps towards creating common competences and capabilities that extend beyond the scope of voluntary cooperation. Simultaneously, they reinforce the legitimacy of the assertion that security is a good with a European dimension that requires an equitable distribution of costs among member states (Dorussen et al., 2009; Thielemann, 2012).

Fuest and Pisani-Ferry (2019) point out that the provision of European public goods has not only an economic but also a political significance. It enhances the legitimacy of the European project because citizens see the tangible benefits of common policies. In the case of security, this effect is particularly pronounced: border protection, cybersecurity, and the fight against organised crime are areas where citizens directly perceive the added value of European cooperation. In this way, security becomes not only a key public good but also an integrating element that contributes to the Union's stability and cohesion.

The conception of security as a European public good is reflected in the specific policies and institutional mechanisms that the EU has progressively built. One of the key areas is border protection and migration. The Schengen Area, founded on the free movement of persons, created the necessity for common external border management. The response was the strengthening of the Frontex agency, which has transformed into the European Border and Coast Guard with a mandate to coordinate and support member states in protecting external borders (Raimondo, 2024). Common border management possesses the character of a public good: if the borders of one member state are better protected, the security of the entire Union increases. According to Kellerhals et al. (2022), the COVID-19 pandemic, as well as the migration crises of 2015 and 2021, demonstrated that the effective management of migration and border protection necessarily require European coordination, otherwise leading to chain problems that threaten internal security.

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Another crucial area is police and judicial cooperation. The establishment of Europol and Eurojust has enabled a more effective fight against organised crime, human trafficking, and terrorism. These institutions function as platforms for information exchange, investigation coordination, and support for national authorities. Security threats in the digital environment, such as cyber-attacks or the misuse of online spaces for the spread of extremism, have led to the adoption of pan-European cybersecurity frameworks (Trimintzios et al., 2024), such as the NIS2 Directive, which introduces stricter resilience requirements for critical infrastructure (Digital Europe, 2025). Cybersecurity is a typical example of a public good, as attacks targeting one member state can have a domino effect on the entire Union.

Civil protection and crisis management represent another dimension of common policies. The Union Civil Protection Mechanism enables a coordinated response to natural disasters, technological accidents, or humanitarian crises (European Commission, 2025). This has been demonstrated in practice, for instance, by the deployment of European teams to extinguish extensive fires in Greece, Portugal, and Spain, as well as by joint deliveries of medical supplies during the COVID-19 pandemic. This mechanism proves that European solidarity in the security domain is not merely a theoretical concept but a concrete manifestation of the joint provision of a public good.

All these policies confirm that security has become an inseparable part of the European project and that its provision has assumed the character of a European public good. The aforementioned examples of common policies indicate that the EU has progressively positioned itself as an active security provider in areas where national solutions encounter limitations. Simultaneously, they highlight the growing importance of solidarity and coordination among member states. However, the question remains as to how effective these mechanisms are and what political and institutional challenges impede their full development. Precisely these issues will be the subject of the following chapter, which will focus on the political and institutional challenges of securing security as a public good in the EU.

4. Political and Institutional Challenges of Securing Security as a Public Good in the EU

The provision of security as a public good within the European Union faces specific political and institutional obstacles that are directly connected to the nature of the European integration project (Walker, 2020). Unlike national states, where the monopoly on the provision of security is vested in state power, in the EU this competence is distributed across multiple levels—national, European, and in some cases, global. The fragmentation of competences between member states and European institutions thus constitutes one of the most fundamental problems (Gruarin et al., 2025).

Competence fragmentation is evidenced by the fact that member states traditionally retain dominant powers in the areas of internal order, justice, and defence, while the EU primarily holds coordinating and supplementary powers (Demke et al., 2020). The result is a multi-level governance structure for decision-making, which often leads to inefficiency and a delayed response to security threats. While agencies such as Europol, Frontex, and Eurojust can provide support and coordination, they lack full executive authority to act independently of the member states. This means that crisis responses—whether to terrorist attacks, migration flows, or cyber-attacks—are conditioned by the political will of individual governments and their willingness to share information, capacities, and resources.

This fragmentation also creates an asymmetry in expectations and responsibilities. EU citizens perceive security as a core value that the Union should provide, yet the institutional framework is currently not adequately equipped to do so. As Bossong and Rhinard (2013) note, this mismatch between expectations and real competences generates a legitimacy deficit and contributes to political tensions between the national and European levels. Member states are often ambivalent—on the one hand, they demand a stronger European response, but on the other, they refuse to cede further powers to Brussels (Maurer, Wright, 2020).

Fragmentation also has practical consequences in the form of duplicative or uncoordinated policies. For example, in the area of cybersecurity, various parallel national strategies and institutions exist, and their harmonisation at the European level is still only in its initial stages (ENISA, 2025). Similarly, in border

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protection, differences persist in technical capabilities, legislative frameworks, and approaches to migration among individual member states, which complicates the effective functioning of the Schengen Area (Fürst, 2024). The result is an uneven level of security across the Union, which undermines citizen confidence in European solutions.

One of the most crucial challenges for the provision of security as a public good in the EU is the risk of the free-rider problem and uneven contribution. This phenomenon is an inherent feature of all public goods, but it is acutely manifested in the context of security. As Bossong and Rhinard (2013) point out, because security possesses the characteristics of a non-excludable and non-rivalrous good, member states tend to minimise their own contributions and rely on security being guaranteed to them thanks to the investments and measures of others.

In the internal domain, this problem is evident, for example, in border protection. Countries on the EU's external border face a greater burden in managing migration and cross-border crime, and their capacities are often insufficient (Bakardjieva Engelbrekt et al., 2024). Other member states that do not face the same immediate pressure have less incentive to invest in joint solutions. The outcome is an imbalance in the distribution of costs and benefits. While the benefits of the free movement of persons accrue to all, the costs of border protection are primarily borne by the frontline states. This situation leads to disputes over solidarity and financial mechanisms that should compensate for the disproportionate burden.

In the area of defence and external security, the free-rider risk is even more pronounced. Some member states systematically underfund their defence budgets and rely on security guarantees from NATO or the investments of stronger European partners (Knezović, Tkalec, 2025). This phenomenon has long been subject to criticism, particularly from the United States, which highlighted that European allies were not meeting the target of 2% of GDP for defence (Ellyatt, 2018; Davidson, 2023). Within the EU itself, there is consequently an ongoing debate about the need for a fairer distribution of costs and mechanisms that would incentivise member states to invest more in common projects.

Uneven contribution is also evident in police and judicial cooperation. Some states are more willing to share intelligence information and engage in joint investigations, while others approach this cooperation selectively. The consequence is a differential level of integration and trust among member states. From the perspective of public goods provision, this is a problem of "partial contribution", where only a fraction of actors invests in the common system, while others profit from it without a comparable input.

Such behaviour not only undermines the effectiveness but also the legitimacy of the European security project. If citizens perceive that certain states' profit from common policies without contributing equitably, it erodes trust in the principle of solidarity, which is fundamental to European integration (Pornschlegel, 2021). Therefore, proposals are increasingly being put forward to introduce conditionality in funding and to create mechanisms that would sanction states with low contributions or those refusing to cooperate. Bossong and Rhinard (2013) emphasise in this context that only an equitable distribution of costs can ensure the sustainability of security as a European public good.

One of the most significant impediments to the provision of security as a public good at the European Union level is limited financial resources. The EU budget has long been set at a relatively low level—approximately one per cent of the member states' Gross National Income. Compared to national budgets, this share is negligible, with security and defence expenditure remaining predominantly under the competence of member states. This means that European institutions possess only limited means to implement their own policies and projects in the security field (Fuest & Pisani-Ferry, 2019).

This situation creates the undersupply of security at the European level. Although there is broad consensus that many threats—from cyber-attacks and terrorism to hybrid threats—require supranational solutions, the available EU financial instruments are often fragmented, short-term, and insufficient. The European Defence Fund (EDF), the Permanent Structured Cooperation (PESCO), and internal security funds represent a step forward, yet their scope is limited compared to the ambitions declared by member states in political strategies. The budgetary

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disproportion between citizen expectations and the EU's actual capacities creates a trust deficit and reinforces the arguments of Eurosceptic actors who question the Union's ability to secure key public goods such as security and defence (Mejino-López, Wolff, 2024; Hildebrand et al., 2025).

A watershed moment was the launch of the NextGenerationEU (NGEU) instrument in 2020, established in response to the COVID-19 pandemic (European Union, 2025). This substantial funding package, exceeding €750 billion, demonstrated the EU's capacity to mobilise resources on a scale previously considered unattainable. Although NGEU was not primarily focused on security, it established a precedent for common financing through debt instruments, which may have implications for future security policy. Consequently, some authors (Anev Janse et al., 2025) speak of the potential for a "security-oriented iteration of NGEU" that would facilitate collective investment in shared infrastructure, cyber resilience, and security research. Such an approach could help overcome fragmentation and the differential contribution of Member States.

However, the financial challenges do not merely concern the overall volume of funding, but also the mechanism of resource allocation. The European budget is often the result of trade-offs between Member States that prioritise the financing of legacy policies, such as agriculture, at the expense of investments in security (Abalasei, 2024). This leads to a situation where security programmes are under-resourced and must operate within the framework of constrained grant schemes. Simultaneously, there is a lack of stable and predictable mechanisms to allow for long-term planning regarding security and defence capabilities and capacities.

Funding challenges, therefore, constitute a central policy dilemma: if security is to be genuinely understood as a European public good, then it is imperative to establish adequate funding instruments and a common budgetary framework that moves beyond *ad hoc* initiatives. Failing this, the EU will inevitably encounter limitations that will undermine its credibility as a security provider and reinforce tendencies toward renationalisation (Guntram et al., 2025; Dermine, 2025).

One of the greatest challenges in providing security as a public good within the European Union is the nexus between the internal and external dimensions of security. Traditionally, these two spheres were viewed separately: internal security encompassed policing, justice, and public order, while external security was associated with foreign and defence policy. In a globalised and technologically interconnected world, however, this boundary is gradually diminishing. Crises and threats now propagate in chain reactions that simultaneously impact both the internal and external environments (Trauner, 2011; Deubner, 2016; Vasiliauskienė, 2024; Mafart, 2025).

The European Union has responded to this reality through a series of strategic documents, the most recent being the ProtectEU initiative (2025). This strategy underscores that 21st-century security cannot be maintained solely through traditional instruments of internal control or national defence but requires a holistic approach that integrates internal and external policy realms. Migration, terrorism, cyber threats, hybrid attacks, and energy dependence are typical examples of threats that cannot be categorised exclusively as internal or external (European Union, 2025; European Commission, 2025; Rehak et al., 2025).

The problem is that the EU's institutional architecture is still predicated on their formal separation. Internal security falls under the purview of the European Commission and the Justice and Home Affairs Council, while external security is the domain of the Common Foreign and Security Policy, the Common Security and Defence Policy, and the European External Action Service. This dualism leads to a lack of coordination and overlapping mandates. The challenge is therefore to create effective operational mechanisms that ensure measures adopted in one sphere are coherent with those in the other.

From the perspective of public goods theory, the integration of internal and external policies is of paramount importance: only this way can an equal level of security be achieved for all EU citizens. If certain states remained exposed to higher risks due to their geographical location or geopolitical situation, it would undermine the principle of solidarity and the uniform provision of the public good. Therefore, the ProtectEU strategy explicitly emphasises that security must be understood as an indivisible good that requires a coordinated internal and external response (European Union, 2025; European Commission, 2025).

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Bridging the gap between internal and external security thus represents not only a practical but also a normative challenge. If security is genuinely to be a European public good, then Member States must overcome traditional jurisdictional divisions and adopt a multi-level governance approach in which internal and external security mutually reinforce each other.

Conclusion

Security as a public good is currently one of the most debated topics in European political and academic discourse. The analysis demonstrates that, within the conditions of a globalised and interconnected society, security cannot be provided exclusively at the national level, as modern threats transcend state borders and affect entire regions or even the entire international system. In this context, the European Union is becoming a unique laboratory where security is being forged as a European public good, founded on the principles of solidarity, collective action, and common financing.

The first key observation stems from the theoretical-economic foundations. Security possesses all the attributes of a public good—it is non-excludable and non-rivalrous (or indivisible), and the investment of one actor generates positive externalities for all others. This leads to the inherent risk of under-provision, uneven contribution, and the free-rider problem. In the European context, these issues manifest as jurisdictional fragmentation and asymmetry among Member States, often complicating the effective operation of common policies. Despite this, providing security at the European level demonstrates greater efficiency and legitimacy than isolated national solutions, particularly in cross-border domains such as migration, cyber-attacks, and climate or health crises.

The second observation relates to institutional development. The European Union has traversed a long trajectory from purely economic integration towards an increasingly powerful role as a security provider. The historical evolution from the Maastricht Treaty, through the Lisbon Treaty, the Global Strategy, and the Strategic Compass, up to the ProtectEU initiative, shows a progressive transfer of competences in the security domain to the European level. While Member States still retain a dominant role, the significance of agencies like Europol and Frontex is growing, as are strategic documents that integrate the internal and external security dimensions into a single framework. Security is thus becoming an integral component of the European project and a pillar of its legitimacy in the eyes of its citizens.

The third fundamental dimension concerns political and institutional challenges. The fragmentation of competences, the exploitation of the free-rider phenomenon, the insufficient share of the EU budget dedicated to security, and the complicated nexus between internal and external security represent barriers that undermine the Union's capacity to fully realise security as a public good. It is evident that without strengthening common fiscal capacity and achieving more effective coordination, the EU will continuously face limitations. Overcoming these barriers necessitates new solidarity mechanisms, innovative financial instruments (such as applying the NextGenerationEU precedent to the security domain), and superior integration across different levels of governance.

Empirical examples—the joint procurement of vaccines, joint energy procurement, the PESCO and EDF initiatives, and the response to the war in Ukraine—confirm that the EU is capable of acting as an active provider of public goods in crisis situations. However, they also reveal that these solutions often emerge only in reaction to acute threats, rather than as part of a long-term sustainable strategy. The key lesson is the need to shift from *ad hoc* reactions to a systematic approach based on risk anticipation and the cultivation of higher levels of resilience.

From a normative standpoint, this implies that security must be understood as a shared commitment of all Member States of the Union, transcending national interests and founded on the principle of solidarity. Political decisions regarding the distribution of competences and resources should therefore not be perceived as a loss of sovereignty but as an investment in collective security. If this approach can be successfully implemented, the EU can function as the "provider of last resort," guaranteeing a minimum level of security for all its citizens.

Looking forward, the key objective for 2030 and beyond will clearly be the strengthening of the Union's strategic autonomy. This does not entail complete independence from partners but the capacity to act autonomously when necessary. Strategic autonomy in security and defence is intrinsically linked to increasing budgetary capacities, developing a joint European defence industrial and technological base, and integrating internal and external policies. The emerging security union will have to respond not only to traditional threats but also to new challenges, such as hybrid attacks, climate insecurity, and geopolitical rivalry among major powers.

In conclusion, security as a public good has become a key pillar of European integration. Its provision transcends the framework of individual Member States and requires novel forms of cooperation, financing, and political coordination. The European Union faces a historic opportunity to transform its security policy to guarantee stability, prosperity, and the confidence of its citizens, even in a period of increasing uncertainty and instability. By fulfilling this role, it will affirm itself not only as an economic and political project but also as the guarantor of one of the most valuable public goods—security.

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ASSESSING BANK EFFICIENCY WITH THE USE OF DEA METHOD: INTEGRATING INTELLECTUAL CAPITAL INTO THE EVALUATIVE FRAMEWORK

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Abstract. Nowadays, banks play a key role in economic development and in ensuring the stability of the financial system; therefore, it is crucial to identify the factors that influence the efficiency of their operations. In the literature, this issue is analysed from two main perspectives: the bank as a producer and the bank as a financial intermediary. In the era of digitalisation and globalisation, competitiveness is no longer based solely on asset size or the growth of basic financial indicators, but rather on the ability to create and utilise intangible resources (intellectual capital). The research aims to assess the efficiency level of banks operating in Poland using two approaches: the traditional production-based efficiency approach and a modern approach based on intellectual capital. The research employs the non-parametric Data Envelopment Analysis (DEA) method, a widely used approach in banking efficiency research. The research sample consists of 10 listed banks on the Warsaw Stock Exchange (WSE), ensuring access to consistent and comparable financial and non-financial data. The selection of this group is based on their significant role in the Polish banking sector and their importance in the sector's transformation processes. The authors test the research hypothesis that the efficiency level of banks operating in Poland differs depending on the adopted evaluation approach — traditional (production-based) or modern, based on intellectual capital. Including intangible resources in the efficiency analysis significantly alters the classification of banks based on their performance. The study period covers the years 2015–2024.

Keywords: bank efficiency; DEA; intellectual capital; producer approach

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1. Introduction

The contemporary banking sector operates in an environment of intense competition, dynamic technological change, and increasing regulatory and market pressures. Processes of globalisation, digitalisation, and the transformation of business models mean that banks are increasingly competing not only in terms of financial capital, but above all through their ability to effectively utilise intangible resources such as knowledge, innovation, and stakeholder relationships (Rosińska-Bukowska, 2022; Khanal, 2023).

The modern financial sector is undergoing rapid technological transformation — automation, data analytics, artificial intelligence (AI), and digital solutions are gaining importance. In banking, electronic and mobile banking systems play a particularly significant role, as they not only enhance operational efficiency but also improve the quality and speed of customer service, thereby shaping the overall customer experience. These

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solutions allow banks to personalise services, manage risks more effectively, and adapt more rapidly to changing market conditions.

The literature emphasises that banking efficiency has become a key determinant of competitiveness, stability, and the ability to create added value in the economy (Klepczarek et al., 2024; Pitre-Cedeño & Herrera-Rodríguez, 2024). Traditionally, the competitiveness of banks was associated mainly with financial factors such as profitability, asset size, market share, or operating costs. Increasingly, however, non-financial factors — those that make up a bank's intellectual capital — are recognised as crucial sources of competitive advantage (Rehman et al., 2022; Rong et al., 2025).

Intellectual capital (IC), understood as a strategic organisational resource, determines the capacity of financial institutions to innovate, adapt to a changing environment, and achieve long-term growth (Le, 2022). It is increasingly recognised as one of the key drivers of competitive advantage in 21st-century banking (Rosińska-Bukowska, 2022; Ullah et al., 2023; Anielak-Sobczak, 2023; Pitre-Cedeño & Herrera-Rodríguez, 2024). Knowledge resources, employee competencies, customer relationships, and internal process efficiency directly affect productivity, service quality, and operational effectiveness. Banks that effectively manage these resources are better equipped to build sustainable competitive positions and respond to digitalisation and cost pressures (Rong et al., 2025).

In this article, a bank's intellectual capital is understood as a resource rooted in the knowledge, skills, and competencies of its employees, as well as in the network of relationships with key stakeholders, including clients, business partners, market competitors, regulators, and shareholders. It shapes a structure of interconnections encompassing organisational processes, innovation activities, and relations with both the internal and external environment of the financial institution. Intellectual capital consists of three interrelated components: organisational capital, which determines the efficiency of internal structures and processes; innovation capital, linked to the ability to develop and implement new technological, product, and process solutions; and relational capital, based on the quality and strength of stakeholder relations (Rosińska-Bukowska, 2022; Rong et al., 2025).

In empirical research, the efficiency of banks is most often assessed using traditional financial indicators such as total assets, equity, the volume of loans and deposits, profitability measures (ROA, ROE), or cost-to-income ratio (CIR). Data Envelopment Analysis (DEA) is one of the most widely used tools in this field, as it enables the evaluation of the relative technical efficiency of decision-making units (DMUs), taking into account multiple inputs and outputs simultaneously, without the need to define a production function ex ante (Khanal, 2023; Delahoz-Domínguez et al., 2024; Klepczarek et al., 2024).

However, most existing studies focus primarily on complex, measurable financial data while overlooking or marginalising intangible resources. They do not account for strategic sources of competitive advantage such as technological innovation, stakeholder relations, ESG, or reputation (Rehman et al., 2022; Rong et al., 2025). For this reason, the literature increasingly calls for extending DEA models to include non-financial variables related to intellectual capital, including innovation, organisational, and infrastructural components.

To date, there remains a lack of extensive research combining traditional DEA efficiency measurements with the dimension of intellectual capital, representing a significant research gap. This study therefore proposes to go beyond conventional financial indicators and incorporate those reflecting the intellectual potential of banks, such as: innovation component (digital technologies, digitalisation, number of mobile and online banking users, AI adoption), relational component (brand image, ESG performance, quality rankings), organisational component (number of employees, branches, wage levels).

Such an approach enables a more comprehensive assessment of the ability of financial institutions to create value and compete in the market, by linking classical technical efficiency with intangible determinants of competitiveness.

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In view of the above, the current objective of this study is to assess the efficiency level of banks operating in Poland using two approaches: the traditional production-based efficiency approach and a modern approach based on intellectual capital. In the article, there was a verified research hypothesis that the efficiency level of banks operating in Poland differs depending on the adopted measurement approach — traditional (intermediary-based and production-based) versus an approach that incorporates intangible factors (intellectual capital).

2. Bank Efficiency – Traditional and Intellectual Capital–Based Approaches

Bank efficiency has long been a key issue in financial sector research. In the classical approach, it was defined mainly in financial and technical terms, which translated into the widespread use of profitability and productivity indicators. Among the most commonly used measures are ROA (Return on Assets), ROE (Return on Equity), the CIR ratio (Cost-to-Income Ratio), and NIM (Net Interest Margin). These indicators enable the measurement of the economic and cost efficiency of banks in relation to the resources utilised (Delahoz-Domínguez et al., 2024; Klepczarek et al., 2024).

Empirical studies have traditionally relied on intermediation and production models. In the intermediation approach, the bank is viewed as a financial intermediary transforming deposits into loans. Inputs typically include operating costs and the value of deposits, while outputs comprise loan values, net financial results, and interest income. In the production approach, the bank is viewed as a producer of financial services, with outputs including deposits, loans, and fee-based income. The most frequently applied efficiency measurement methods in these studies are DEA (Data Envelopment Analysis) and SFA (Stochastic Frontier Analysis), which allow for the estimation of the relative efficiency of decision-making units without the need to specify a production function ex ante (Pitre-Cedeño & Herrera-Rodríguez, 2024).

In recent years, however, there has been a marked shift in the research perspective—from narrowly defined financial efficiency toward a strategic approach that incorporates intangible factors and intellectual capital (IC). Le et al. (2022), in a study of 26 commercial banks in Vietnam from 2007 to 2019, demonstrated that intellectual capital components, such as human capital (HC) and structural capital (SC), have a significant impact on bank efficiency, as measured using DEA. Notably, banks with higher HC levels achieved higher ROA and ROE ratios even when their asset levels were comparable.

Similarly, Rehman et al. (2022), analysing the banking sector in Pakistan, confirmed a positive relationship between intellectual capital efficiency (measured using the VAIC index) and banks' financial performance. The most substantial effects were observed for CEE (Capital Employed Efficiency) and HCE (Human Capital Efficiency), highlighting that the management of human resources and financial capital is a key source of competitive advantage for financial institutions. Likewise, Zheng et al. (2022) demonstrated that IC affects not only efficiency but also banks' risk profiles; institutions with higher IC levels exhibited greater resilience to external shocks and improved financial stability. In European research, Rong et al. (2025) applied an extended DEA model that included both financial indicators and IC components. Their findings revealed that incorporating variables such as the number of digital banking users, technological investment, and ESG indicators yields significantly different efficiency assessments compared to traditional models. Banks with strong relational and innovation capital achieved higher efficiency scores despite having smaller financial assets.

These findings confirm that bank efficiency is multidimensional, and financial indicators alone reflect only part of an institution’s true potential. Increasingly, efficiency is understood as the capacity for technological adaptation, knowledge management, and building stakeholder relationships. In practice, this means a shift away from static efficiency measurement toward dynamic models that allow researchers to analyse not only the level of efficiency but also the pace of its change over time. One example is the use of the Malmquist Index, applied by Delahoz-Domínguez et al. (2024) to assess efficiency dynamics in the Latin American banking sector.

Modern research, therefore, confirms that an effective assessment of bank efficiency requires the integration of traditional financial indicators (ROA, ROE, CIR, NIM) with qualitative factors (HCE, SCE, CEE, digitisation and ESG indicators), emphasising the growing importance of intangible measures. This approach provides a

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more accurate reflection of the real ability of financial institutions to compete and adapt in a globally transforming digital environment.

3. DEA Method - Theoretical Basis

In the literature on the subject, the DEA method is used to determine the efficiency of banking sectors or banks from a given group. The efficiency indicator calculated using this method is relative efficiency (Gulati et al., 2023; Istaiteyeh et al., 2024). The DMU group under research may include similar entities capable of transforming inputs into outputs (Hsiung et al., 2025). The results obtained by DMU are compared to the results of the other DMUs (Shaik, 2022). In this way, it is possible to rank the efficiency of DMUs for the research group (Patra et al., 2023). Efficiency calculated using the DEA method takes values from the range [0, 1], with DMUs with an efficiency index of 1 being defined as efficient (Berhe, 2025). In the DEA method, more than one DMU can be efficient. This does not mean that efficient DMUs have the same input and output values or that they use the same solutions (Hasannasab et al., 2024). Some efficient DMUs can serve as benchmarks for inefficient DMUs (Cui et al., 2025).

The literature on the subject categorises DEA models based on economies of scale and input or output orientation. The first criterion is the orientation of the model, which may aim to maximise outputs or minimise inputs (Demircioğlu & Özgüner, 2022). It is also possible to use a model without orientation. Approaches to economies of scale include models with constant economies of scale (CCR model) (Flores-Ureba et al., 2024) and models with variable economies of scale (BCC model, models with non-increasing economies of scale, models with increasing economies of scale, models with non-decreasing economies of scale (Kosmaczewska, 2011). This division is supplemented by the definition of efficiency as radial (referring to all examined inputs or all examined outputs) or non-radial (in an input-oriented model, it is examined separately for each of the inputs included in the research, while in an output-oriented model, efficiency is examined separately for each of the outputs included in the research) (Wolszczak-Derlacz, 2013).

The literature on the subject describes many models of the DEA method. The CCR model is the first DEA model. It was developed by Charnes, Cooper, and Rhodes. The authors of the first DEA model proposed using a weighted sum of inputs and a weighted sum of outputs to calculate efficiency (Amirteimoori, 2025). In the CCR model, the efficiency indicators for the input-oriented model and the output-oriented model are inverses of each other. This model assumes constant returns to scale. Efficiency in this DEA model can be defined as follows (Baran, 2007):

$$Efficiency\ (\theta) = \frac{\sum_{r=1}^{m} \mu_r\ Output_r}{\sum_{i=1}^{n} \nu_i\ Input_i}$$

where:
m - number of outputs,
n - number of inputs,
μ_r - the intensity of individual outputs,
ν_i - the relative importance of individual inputs.

Another DEA model is the BCC model (named after its authors: Banker, Charnes and Cooper), which is an extension of the CCR model that takes into account variable economies of scale (Fonseka & Al Farooque, 2024). This means that researchers using the BCC model assume that DMUs are affected by market events that are beyond their control and may cause economies or diseconomies of scale. The BCC model takes variable economies of scale into account, but does not specify what type they are. In the BCC model, the efficiency indicators for the input-oriented model and the output-oriented model are not inverses of each other. The literature recommends using this model to measure the efficiency of developed banking sectors or banks operating within them (Titko, Stankeviciene, & Lace, 2014). Efficiency in the DEA method is determined using an objective function (θ), in which weights act as decision variables. The optimal objective function is inherently linked to the determination of weights (μ_r; ν_i). These weights enable the determination of a set of benchmarks (so-called reference objects). This makes it possible to determine to what extent a given entity

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should reduce its inputs while maintaining the level of outputs (input-oriented DEA) or increase outputs at the current level of inputs (output-oriented DEA) (Masternak-Janus & Rybaczewska-Błażejowska, 2016).

4. Methodology and Course of the Research

The research included banks listed on the Warsaw Stock Exchange (Alior Bank, BNP Paribas, mBank, Citi Handlowy, ING Bank, Millenium Bank, PEKAO Bank, PKO BP, Santander Bank, BOŚ). The research period spanned from 2015 (the year mobile banking users began to be reported; earlier data do not cover the entire group) to 2024 (the latest available data). The research was conducted using a non-radial BCC model focused on expenditure. The choice of model was due to the specific nature of the group of entities under research, which is influenced by factors outside the Polish banking sector. On the other hand, the use of an input-oriented model made it possible to identify entities that were effective with the inputs used. The research compared two approaches to bank efficiency. The first, referred to as traditional, was an approach to bank efficiency understood as a producer. The second approach involved assessing bank efficiency in terms of its intellectual capital.

After examining simple statistical methods and correlations, the research took into account:

- inputs: Operating costs, Equity, Number of bank branches,
- outputs: Loans, Deposits, Net profit.

After examining simple statistical methods and correlations, the research took into account:

- inputs: Operating costs, Training costs, Number of bank branches, Employee benefits/number of employees,
- outputs: Złoty Bankier – measure, Number of clients actively using online banking/number of clients.

The research of the efficiency of banks listed on the Warsaw Stock Exchange was divided into three stages. The first stage involved determining the average efficiency of banks in terms of the bank as a producer and efficiency indicators in terms of individual inputs. The second stage involved determining the efficiency of banks in terms of intellectual capital and efficiency indicators in terms of individual inputs. In the third stage, the results indicate which banks were effective in particular approaches, and whether there were similar groups of efficient banks in both approaches.

5. Results

Tables 1 and 2 present the results of the efficiency analysis of banks listed on the Warsaw Stock Exchange in the years 2015-2024, using an approach that considers the bank as a producer. Table 1 shows the results of non-radial efficiency, i.e., the average obtained from efficiency based on individual inputs. Further, Table 2 presents the results of efficiency coefficients for individual inputs, allowing for the identification of which inputs contributed to the inefficiency of certain entities.

Table 1. Summary of the results of the research on the effectiveness of banks operating on the Warsaw Stock Exchange from the perspective of the bank as a producer

Bank	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Alior Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,71	0,76	1,00
BNP Paribas	1,00	1,00	0,81	1,00	0,58	1,00	0,63	0,60	0,63	0,62
mBank	0,66	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,73	1,00	1,00	0,77	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	1,00	1,00	1,00	0,75	0,90	0,67	0,76	0,63	1,00	1,00
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Santander Bank	1,00	1,00	1,00	1,00	0,94	1,00	0,67	1,00	0,76	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Source: Based on research conducted by the authors in the R computing environment using the deaR package, with data from financial statements of the examined banks, reports on the activities of the management boards of the examined banks, NetB@nk Reports on online and mobile banking, cashless payments for the years 2015-2024

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At the end of each year from 2015 to 2024, Citi Handlowy, ING Bank, PKO BP, and BOŚ were effective in the producer bank approach. Each of the banks researched was effective in at least one of the years researched. Banks that achieved an efficiency of less than 0.7 in at least two years of the period researched were considered the least effective in the period researched. These were BNP Paribas (2019, 2021, 2022, 2023, 2024) and PEKAO Bank (2020, 2022). This means that the expenditures incurred by these banks in some years were too high in relation to the results achieved. Table 2 below presents the efficiency results of the entities researched in terms of individual expenditures.

Table 2. Summary of the results of the research on the effectiveness of banks operating on the Warsaw Stock Exchange in the bank as a producer approach in terms of individual expenditures

Bank	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Efficiency in terms of Operating Costs										
Alior Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,73	0,70	1,00
BNP Paribas	1,00	1,00	0,95	1,00	0,45	1,00	0,80	0,84	0,70	0,82
mBank	0,53	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,57	1,00	1,00	0,84	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	1,00	1,00	1,00	0,69	0,99	0,99	0,86	0,71	1,00	1,00
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Santander Bank	1,00	1,00	1,00	1,00	1,00	1,00	0,68	1,00	0,94	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Efficiency in terms of Equity										
Alior Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,73	0,94	1,00
BNP Paribas	1,00	1,00	1,00	1,00	1,00	1,00	0,72	0,61	0,81	0,70
mBank	0,54	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	1,00	1,00	1,00	0,92	0,97	0,63	0,78	0,56	1,00	1,00
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Santander Bank	1,00	1,00	1,00	1,00	0,87	1,00	0,62	1,00	0,61	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Efficiency in terms of the Number of Bank Branches										
Alior Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,68	0,63	1,00
BNP Paribas	1,00	1,00	0,47	1,00	0,29	1,00	0,37	0,36	0,37	0,33
mBank	0,92	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,62	1,00	1,00	0,47	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	1,00	1,00	1,00	0,65	0,73	0,39	0,65	0,61	1,00	1,00
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Santander Bank	1,00	1,00	1,00	1,00	0,95	1,00	0,70	1,00	0,73	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Source: Based on research conducted by the authors in the R computing environment using the deaR package, with data from financial statements of the examined banks, reports on the activities of the management boards of the examined banks, NetB@nk Reports on online and mobile banking, cashless payments for the years 2015-2024

The above information enables the identification of which expenditures contributed to the inefficiency of individual banks. Considering the expenditures incurred in the research, the number of bank branches was the primary cause of inefficiency among the entities examined. The second expenditure that did not turn into the expected results was operating costs. Due to this expenditure, the efficiency ratios for the entities researched in individual years from 2015 to 2024 were not on the efficiency curve in 45 cases (across different entities and years within the research period). Tables 3 and 4 below present the results of the efficiency research on banks listed on the Warsaw Stock Exchange from 2015 to 2024, using an approach that takes intellectual capital into account.

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Table 3. Summary of the results of the research on the effectiveness of banks operating on the Warsaw Stock Exchange, taking into account intellectual capital

Bank	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Alior Bank	1,00	0,84	0,38	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BNP Paribas	1,00	1,00	1,00	1,00	0,62	0,71	0,63	0,63	0,60	0,57
mBank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,68	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	0,76	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,81	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	0,34	0,31	0,33	0,56	0,53	0,40	0,48	0,50	0,43	0,42
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	0,48	0,57	1,00	1,00
Santander Bank	0,59	0,46	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Source: Based on research conducted by the authors in the R computing environment using the deaR package, with data from financial statements of the examined banks, reports on the activities of the management boards of the examined banks, NetB@nk Reports on online and mobile banking, cashless payments for the years 2015-2024

At the end of each year from 2015 to 2024, Citi Handlowy and BOŚ were included in the efficiency approach, taking into account intellectual capital. Each of the banks researched was efficient in at least one of the years studied. As in the case of the producer bank approach, it was assumed that inefficient banks were those that achieved an efficiency below 0.7 in at least two years of the researched period. These were BNP Paribas (2019, 2021, 2022, 2023, 2024) and PEKAO Bank (years from the period 2015-2024). This means that the expenditures incurred by BNP Paribas in some years were too high in relation to the achieved results. In the case of PEKAO Bank, the effects achieved were much lower in relation to the expenditures incurred. Table 4 presents the components of the non-radial efficiency coefficient, i.e., efficiency coefficients in relation to individual expenditures.

Table 4. Summary of the results of the efficiency research of banks operating on the WSE, taking into account intellectual capital in relation to individual expenditures

Bank	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Efficiency in terms of Operating Costs										
Alior Bank	1,00	0,77	0,14	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BNP Paribas	1,00	1,00	1,00	1,00	0,54	0,76	0,62	0,72	0,50	0,45
mBank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,48	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	0,55	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,84	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	0,10	0,03	0,27	0,37	0,33	0,23	0,31	0,29	0,20	0,18
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	0,24	0,29	1,00	1,00
Santander Bank	0,45	0,38	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Efficiency in terms of Training Costs										
Alior Bank	1,00	0,62	0,20	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BNP Paribas	1,00	1,00	1,00	1,00	0,38	0,62	0,20	0,17	0,37	0,27
mBank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,51	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	0,63	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,68	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	0,10	0,14	0,14	0,44	0,39	0,41	0,23	0,24	0,14	0,27
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	0,29	0,84	1,00	1,00
Santander Bank	0,61	0,22	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Efficiency in terms of the Number of Bank Branches										
Alior Bank	1,00	0,96	0,34	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BNP Paribas	1,00	1,00	1,00	1,00	0,89	0,63	0,83	0,94	0,54	0,58
mBank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,90	1,00	1,00

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Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	0,96	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	0,72	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	0,17	0,11	0,11	0,45	0,72	0,34	0,61	0,62	0,39	0,38
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	0,41	0,19	1,00	1,00
Santander Bank	0,33	0,35	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Efficiency in terms of Relation between Employee Benefits and the Number of Bank Employees										
Alior Bank	1,00	1,00	0,83	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BNP Paribas	1,00	1,00	1,00	1,00	0,67	0,82	0,86	0,69	0,97	0,97
mBank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,82	1,00	1,00
Citi Handlowy	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ING Bank	1,00	1,00	1,00	0,90	1,00	1,00	1,00	1,00	1,00	1,00
Millenium Bank	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PEKAO Bank	0,97	0,97	0,79	1,00	0,66	0,62	0,78	0,85	0,97	0,83
PKO BP	1,00	1,00	1,00	1,00	1,00	1,00	0,96	0,96	1,00	1,00
Santander Bank	0,98	0,87	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
BOŚ	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Source: Based on research conducted by the authors in the R computing environment using the deaR package, with data from financial statements of the examined banks, reports on the activities of the management boards of the examined banks, NetB@nk Reports on online and mobile banking, cashless payments for the years 2015-2024

Table 4 contains efficiency coefficients for individual expenditures, allowing for the identification of which expenditures contributed to the inefficiency of certain entities. Taking into account the expenditures included in the research, training costs were the primary cause of inefficiency among the entities researched. The second expenditure that did not translate into the expected results was operating costs.

During the research period, some banks were effective in each of the approaches to effectiveness adopted. In the first year of the research period, the groups of effective entities were almost the same – PEKAO Bank and Santander Bank were effective in the producer bank approach, but ineffective when intellectual capital was taken into account. At the same time, mBank was ineffective in the producer bank approach and effective in the second approach. In 2016, three entities (Alior Bank, PEKAO Bank, Santander Bank) were effective in the producer bank approach, but were not effective in the second approach. In subsequent years of the period under review, the efficiency ratios in the individual approaches to bank efficiency differed in the results achieved by one or two entities. In both approaches, BNP Paribas and PEKAO Bank were inefficient in several years of the research period.

6. Discussion

The findings of this research indicate that incorporating intellectual capital into efficiency assessment models significantly alters the results of DMUs efficiency compared with models based solely on traditional financial indicators. This outcome confirms the growing importance of intangible resources in the banking sector. It simultaneously distinguishes the present research from the existing literature, where DEA analyses predominantly rely on financial data and conventional production-based approaches. In Polish research, such as Mastalerz (2017) and Czerwonka (2019), efficiency assessments rely exclusively on financial variables—assets, deposits, operating costs and loan volumes—without accounting for intellectual capital as a productive input. Similarly, international studies employ classical financial sets of DEA variables: Turkish analyses apply CAMELS indicators (Wang et al., 2024), Serbian studies utilise the intermediation, operating and profitability approaches (Horvat et al., 2022), while a pan-European analysis of 471 banks relies on ROA, capitalisation, liquidity and provisioning measures (Licerán-Gutiérrez et al., 2025).

Asian studies also predominantly focus on financial metrics. Malaysian banks are evaluated using the SE-SBM model with inputs such as deposits, assets and equity, and non-interest income and investment as outputs (Kasim et al., 2019). Chinese studies adopt an extended by-production SBM framework that incorporates undesirable outputs such as non-performing loans (Shi et al., 2023). None of these approaches integrate

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components of intellectual capital. The only research explicitly addressing intellectual capital—conducted on Nigerian listed banks (Olohunlana et al., 2023)—evaluates IC efficiency exclusively, without comparing it against financial efficiency or applying a dual-perspective framework. The present research addresses this gap by adopting a two-track efficiency approach with the use of DEA, which separately assesses financial efficiency and intellectual capital efficiency, enabling the identification of divergences between the two dimensions and demonstrating that banks performing well in traditional DEA models may not necessarily excel in managing intangible resources.

The distinctiveness of this research becomes even more pronounced when juxtaposed with recent analyses on the condition and competitiveness of the banking sector. The study by Iwanicz-Drozdowska and Nowak (2024) examines the competitiveness of the Polish banking sector relative to EU members between 2004 and 2022, focusing on financial indicators such as ROE, net interest margin, cost-to-income ratio, capital adequacy and sector concentration measures. Although the authors highlight the rising role of digitalisation and technological advancements in shaping bank competitiveness, their research neither applies DEA methodology nor integrates intangible resources into the analytical framework. This reinforces the importance of the present research's approach: intellectual capital—comprising knowledge, innovation, organisational capabilities, and customer relations—has become a strategic determinant of contemporary banking performance and should be explicitly incorporated into efficiency models.

The temporal and contextual scope further differentiates this research from prior research. While international studies mainly cover pre-pandemic periods (e.g., Malaysia 2004–2013; Serbia 2008–2019; Poland 2013–2018), the present analysis spans 2015–2024—a period marked by intense digital transformation, the COVID-19 pandemic and dynamic regulatory and technological shifts. Additionally, whereas most earlier studies examine sectoral or aggregated banking performance, the present research focuses on individual publicly listed banks and applies a richer set of inputs and outputs, including non-financial, intangible variables.

In summary, this research adds significant value to the literature by demonstrating that traditional use of DEA models—relying exclusively on financial measures—does not fully capture the organisational and innovative capabilities of modern banks. Integrating intellectual capital into an efficiency approach reveals alternative sources of competitive advantage and provides a better explanation of heterogeneity in bank performance in increasingly digitalised environments. The simultaneous application of financial DEA and IC-DEA constitutes a novel methodological and empirical contribution that clearly differentiates this research from prior national and international studies, underscoring its innovative character.

Conclusions

The findings of this research indicate that incorporating intellectual capital into efficiency assessment models significantly alters the results of DMUs efficiency compared with models based solely on traditional financial indicators. This outcome confirms the growing importance of intangible resources in the banking sector and simultaneously distinguishes the present research from the existing literature, which predominantly relies on DEA analyses that use financial data and conventional production-based approaches. In Polish research, such as Mastalerz (2017) and Czerwonka (2019), efficiency assessments rely exclusively on financial variables—assets, deposits, operating costs and loan volumes—without accounting for intellectual capital as a productive input. Similarly, international studies employ classical financial sets of DEA variables: Turkish analyses apply CAMELS indicators (Wang et al., 2024), Serbian studies utilise the intermediation, operating and profitability approaches (Horvat et al., 2022), while a pan-European analysis of 471 banks relies on ROA, capitalisation, liquidity and provisioning measures (Licerán-Gutiérrez et al., 2025).

Asian studies also predominantly focus on financial metrics. Malaysian banks are evaluated using the SE-SBM model, which takes into account inputs such as deposits, assets, and equity, as well as non-interest income and investment, with outputs including these factors (Kasim et al., 2019). Chinese studies adopt an extended by-production SBM framework that incorporates undesirable outputs such as non-performing loans (Shi et al., 2023). None of these approaches integrates components of intellectual capital. The only research explicitly addressing intellectual capital, conducted on Nigerian listed banks (Olohunlana et al., 2023), evaluates IC

efficiency exclusively, without comparing it to financial efficiency or applying a dual-perspective framework. The present research addresses this gap by adopting a two-track efficiency approach using DEA, which separately assesses financial efficiency and intellectual capital efficiency, enabling the identification of divergences between the two dimensions and demonstrating that banks performing well in traditional DEA models may not necessarily excel in managing intangible resources.

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The temporal and contextual scope further differentiates this research from prior research. While international studies mainly cover pre-pandemic periods (e.g., Malaysia, 2004–2013; Serbia, 2008–2019; Poland, 2013–2018), the present analysis spans 2015–2024—a period marked by intense digital transformation, the COVID-19 pandemic, and dynamic regulatory and technological shifts. Additionally, whereas most earlier studies examine sectoral or aggregated banking performance, the present research focuses on individual publicly listed banks. It applies a richer set of inputs and outputs, including non-financial, intangible variables.

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DATA-DRIVEN ASSESSMENT OF DIGITAL MATURITY IN INDUSTRIAL ENTERPRISES: A MULTI-LAYER MODEL FOR STRATEGY AND TRANSFORMATION READINESS

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Abstract. Industrial firms continue to experience substantial obstacles when attempting to adopt and operationalise key Industry 4.0 technologies. These challenges are often rooted in fragmented decision-making, inconsistent alignment between digital initiatives and corporate strategy, and limited analytical tools for verifying the actual state of organisational readiness. This paper proposes and validates a structured methodology for assessing the conformity of organisational processes with a generic digital maturity model through a multi-stage, evidence-based approach. The method integrates a systematic literature review, in-depth examination of internal corporate documentation, and a weighted matrix analysis applied to empirical data from an industrial firm. This procedure produces both an overall digital maturity index and a detailed layer-based profile covering strategic alignment, cost management, human resource capabilities, and implementation practices. The study introduces the concept of a "digital strategic centre of gravity" as an analytical instrument for identifying disproportions across maturity layers and tracing their causal mechanisms. This indicator enables the formulation of targeted, actionable recommendations aimed at restoring balance in the digital transformation trajectory. Empirical results reveal that the predominant constraints arise from insufficient alignment between digital and corporate strategies, weak cost governance mechanisms, and substantial competency gaps within the workforce. The proposed methodology moves beyond subjective self-assessments by offering a quantified, data-driven verification procedure. In doing so, it enhances diagnostic precision, strengthens strategy execution, and provides managers with a replicable framework for guiding evidence-based digital transformation.

Keywords: digital maturity; Industry 4.0; strategic management; manufacturing; balanced scorecard

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1. Introduction

In the current era of Industry 4.0, industrial enterprises face the need to integrate the principles of digital transformation into both their core and supporting processes (Lenart-Gansiniec, 2019; Liebrecht et al., 2021; Šafránek & Mikle, 2022). The integration of these principles has become an essential prerequisite for maintaining competitiveness in an increasingly dynamic and technology-driven market environment. Nevertheless, digitalisation does not exclusively generate progress it simultaneously introduces new organisational challenges and implementation barriers (Angelopoulou et al., 2020; Kuba & Milichovský, 2019). Among the most significant barriers are the high initial costs required to obtain and integrate the necessary hardware and software solutions, together with the insufficient digital maturity of organisations (Mon & Del Giorgio, 2022; Ratnasingam et al., 2020). Digital maturity itself can be interpreted through two complementary

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dimensions: the adequacy of an organisation's strategic approach to digital transformation and the overall digital literacy level of its workforce. An incomplete or incoherent digitalisation strategy often results in the inefficient allocation of financial resources or an inaccurate assessment of the organisation's current digital status (Halse & Jæger, 2019; Di Bona et al., 2021). When the digital strategy is poorly aligned with the organisation's overall strategic direction, instead of improving performance, digital initiatives may even deteriorate operational efficiency or negatively affect the financial situation, employee motivation, or competence development (Tay et al., 2021). Given that digitalisation is closely intertwined with investment decision-making, LEAN management, quality control, and logistics, its adoption must be approached holistically, encompassing both value-creating and support processes (Naciri et al., 2022; Domanižová et al., 2020). A clear understanding of a company's digital maturity thus represents a crucial prerequisite for overcoming these obstacles. Assessing the current state of maturity enables organisations to adapt their strategic goals, design training programmes that enhance employees' readiness for new technologies, and allocate financial resources more effectively (Cejpek et al., 2025). Therefore, identifying the relationship between an organisation's achieved digital maturity level and its strategic management tools becomes vital. One suitable tool for establishing such a link is the Balanced Scorecard framework, which facilitates the monitoring of digitalisation initiatives, the assignment of responsibilities, and the enhancement of organisational motivation (Ghouri et al., 2021; Talír & Chytilova, 2024). Accordingly, the primary objective of this paper is to assess the level of digital maturity within an industrial organisation and to propose strategic remedial actions based on a generic digital maturity model.

2. Review of literature and Research objective

Digital transformation and organisational readiness represent essential pillars of the Fourth Industrial Revolution, commonly referred to as Industry 4.0 (Zonta et al., 2020; Bigliardi et al., 2022; Isidora et al., 2022). Industry 4.0 encompasses a broad spectrum of technological enablers, including adaptive robotics, data analytics and artificial intelligence, simulation, integrated systems, communication infrastructures, cybersecurity, cloud computing, additive manufacturing, virtual and augmented reality, sensors and actuators, RFID/RTLS, and mobile platforms. The integration of these technologies into organisational processes has therefore become a central topic of contemporary research. Numerous authors, including Soomro et al. (2021) and Suleiman et al. (2022), have examined how industrial organisations operationalise digital transformation under the Industry 4.0 paradigm.

Issa et al. (2018) introduced a conceptual framework for assessing digital transformation progress by defining four maturity stages, ranging from non-systematic digital initiatives to fully integrated inter-organisational value chains. Their model is structured into six implementation milestones. Göklap and Martinez (2021) similarly proposed a six-level maturity framework, developed from an extensive literature analysis, ranging from organisations with no digital transformation activity to those operating autonomous, data-driven value chains supported by predictive analytics. Further contributions include the 6Ps model by Spaltini et al. (2022) and Ecer et al. (2024), which evaluates maturity across six dimensions: products, processes, platforms, people, partnerships, and performance. This model is supported by a detailed evaluation matrix and network visualisations. Similarly, the SIMMI 4.0 model (Schumacher et al., 2019) classifies organisations across five maturity levels and offers practical guidance for progression.

Beyond classification-based models, quantitative approaches also exist. Schumacher et al. (2016) introduced a numerical assessment model comprising 62 criteria across nine organisational dimensions. While offering precise scoring, the reliance on self-assessment introduces subjectivity. Other frameworks share comparable limitations.

Alternative perspectives focus on readiness and competencies. Brozzi et al. (2021) developed a Key Readiness Indicator model, derived from strategy, awareness, and competence domains, tailored specifically for SMEs. Steinlechner et al. (2021) and Mihajlovic et al. (2025) conceptualised digital maturity through employee competences, proposing the DigiCoM model, which evaluates 49 attributes related to digital content, human–machine interaction, human–human interaction and personal development. Machine-learning-based analyses also demonstrate the field's thematic diversity (Lee et al., 2021), while comparative studies, such as those by Kartal et al. (2018), highlight methodological fragmentation across maturity models. This fragmentation

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contributes to organisations' difficulty in evaluating their actual maturity level (Schumacher et al., 2019), which in turn impairs investment decisions and transformation planning. Various authors have therefore focused attention on barriers, risks, and causal factors influencing transformation processes (e.g., Raj et al., 2020; Tamvada et al., 2022; Cheng et al., 2025).

The literature consistently stresses that digital transformation is inherently systemic, interdependent and cross-functional (Dossou et al., 2022; Elafri et al., 2022). Synergies with established managerial paradigms such as LEAN have been demonstrated (Satoglu et al., 2018), and Industry 4.0 technologies have been shown to reshape supply chain dynamics (Enrique et al., 2022; García-Reyes et al., 2022), organisational agility (Akhtar et al., 2018) and production planning processes (Colangelo et al., 2022).

3. Methodology

Building on the conceptual and methodological limitations identified in the literature, this research adopts an applied empirical case study design supported by elements of logical and comparative analysis. The aim is to provide a verifiable, data-driven procedure for assessing the digital maturity of an engineering manufacturing organisation and to translate the diagnostic results into strategic guidance. In line with the gaps highlighted above, the study formulates two research questions:

- RQ1: What analytical tool can be used to verify the alignment of organisational processes with the key indicators of a generic digital maturity model?
- RQ2: How can the achieved maturity level be translated into subsequent strategic activities of the organisation?

The study builds on two complementary inputs. First, it extends a conceptual model of organisational digital maturity tailored to industrial contexts, refining it into a verifiable framework (Talír & Chytilová, 2024). Second, it utilises internal operational data from a Czech engineering manufacturing enterprise to demonstrate the verification procedure through two digitalisation projects*: Factory Monitor* (an IoT-based autonomous data acquisition system) and *TrackingApp* (an operator-driven digital reporting system). The combination of automated and manual process data ensures coverage across the production flow. The organisation remains anonymised, and results are analytically rather than statistically generalised.

Generalisation of the Digital Maturity Model
Following the literature's identified need for sector-specific yet generalisable frameworks, the model is adapted for engineering manufacturing. The generalisation synthesises (i) consolidated evidence from maturity literature and (ii) practitioner insights derived from the model organisation's processes. Validity draws on triangulation across literature, enterprise data and structured reasoning, while reliability is ensured through transparent methodological documentation.

Operationalisation Through Key Indicators and Compliance Verification
Each model element is translated into process-oriented key performance indicators (KPIs), which are classified as either attributive or relative. Weighted matrix analysis reflecting both indicator and layer weights quantifies the degree of compliance. Relationship strengths are rated on a five-point scale and transformed into coefficients aggregated into layer scores and an overall maturity index. Visual representations include radar plots and a five-stage maturity classification. Reliability is increased through an explicit coding rubric and replicable calculation steps.

Strategy Optimisation Based on Maturity Knowledge
To address the literature-identified gap regarding strategic applicability, the maturity profile is converted into managerial insights using the concept of a *digital strategic centre of gravity*. This diagnostic tool identifies imbalances between maturity layers and supports targeted corrective actions, drawing on Bowman's strategic logic. Selected KPIs are embedded within a Balanced Scorecard structure to ensure ownership, monitoring, and incentive alignment, establishing a repeatable loop that connects assessment, strategy formation, and execution.

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4. Results and discussion

Calculating the digital maturity of an organisation

To evaluate the degree of fulfilment of the individual indicators of the proposed model, the weighted matrix analysis method was applied. This approach enables the determination of both qualitative and quantitative relationships between the organisation's processes and the respective sub-processes (pillars) of the digital maturity model. The horizontal axis of the matrix represents the key sub-processes of digital maturity, while the vertical axis lists the analysed organisation and its implemented projects. The matrix therefore expresses the degree of compliance between the organisation's actual processes and the reference model processes.

For evaluation, the processes were divided into two principal categories according to their measurability: processes measurable by attributive indicators, which are binary in nature and express whether a given condition is fulfilled or not fulfilled, and processes measurable by relative indicators, which are expressed as a percentage of the target level of achievement and therefore allow for a more detailed differentiation of the degree of compliance with the model criteria. Attributive indicators were represented graphically by two extreme values only: no relationship (the condition not met) or a very strong relationship (the condition fully met). Relative indicators were classified according to the level of fulfilment achieved and assigned a graphical symbol representing one of five degrees of relationship strength: none, weak, moderate, strong, and very strong, as shown in Table 1. These degrees were then converted into corresponding coefficients of 0.00, 0.25, 0.50, 0.75, and 1.00, respectively, allowing for a precise numerical transformation of the graphical representation. The respective intervals of compliance were defined as follows: 0–24.9 %, 25–49.9 %, 50–74.9 %, 75–99.9 %, and 100 % +.

Table 1. Graphical transformation of indicators

Symbol	Description	Relative indicator	Attributive indicator
✖	No relationship; coef. 0,00	0 - 24,9 %	No
△	Weak relationship; coef. 0,25	25 – 49,9 %	
○	Moderate relationship, coef. 0,50	50 – 74,9 %	
◉	Strong relationship, coef. 0,75	75 – 99,9 %	
◉	Very strong relationship, coef. 1,00	100% +	Yes

Source: the authors

The conversion between numerical and graphical form provides a transparent overview of how the individual organisational processes correspond to the digital maturity model.

Table 2 illustrates how symbols were assigned to individual processes or projects according to this system. For attributive indicators, only two extremes were possible: no or a very strong relationship, depending on whether the criterion was met. For relative indicators, the achieved percentage of target fulfilment determined the respective level of relationship strength, following the classification system in Table 1. For example, a process achieving 65 % compliance with a target value was classified under the moderate relationship level, as it fell within the range of 50–74.9 %. This rule-based classification eliminates ambiguity and excessive subjectivity typical of self-assessment frameworks by ensuring that a process achieving only 49 % cannot be assessed as moderate but remains in the weak category. This strictness enhances consistency and comparability, while motivating continuous improvement.

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Table 2. Matrix analysis of relationship strength

	Strategic layer					Cost layer						Personnel layer			Implementation layer				
	The existence of a digital strategy	*Degree of fulfilment of the I4.0 concept*	*Investment estimate*	*Investments in AOP*	*Achieving implementation milestones*	*Portfolio of technical options*	*Portfolio selection*	*Project creation*	*Investment plan*	*ROI in the first year of operation*	*Financial plan*	*Definition of the digital mature worker profile*	*Staff status*	*Qualification level of staff*	*Cooperation with the supplier*	*Purchase price deviation*	*Installation status*	*Test phase action plan*	*Starting the sharp phase*
Project	KPI I.I.	KPI I.II.	KPI I.III.	KPI I.IV.	KPI I.V.	KPI II.I.	KPI II.II.	KPI II.III.	KPI II.IV.	KPI II.V.	KPI II.VI.	KPI III.I.	KPI III.II.	KPI III.III.	KPI IV.I.	KPI IV.II.	KPI IV.III.	KPI IV.IV.	KPI IV.V.
Factory Monitor	✖	◉	◉	◉	○	✖	✖	✖	✖	△	✖	✖	◉	◉	◉	◉	◉	◉	◉
TrackingApp	✖	◉	◉	◉	◉	◉	◉	✖	✖	◉	✖	✖	◉	◉	◉	◉	◉	◉	◉

Source: the authors, data of the company xyz

Since the evaluation of organisational processes' compliance with the digital maturity model is performed using the weighted matrix analysis, it is essential to define appropriate weights for both individual indicators and the model's layers. The weighting system ensures that critical elements exert proportionally greater influence on the final maturity score and that the result reflects not only the extent of compliance but also the strategic significance of each process. Digital maturity is thus perceived as both a layer-specific and a composite organisational characteristic. The weighting rules are straightforward: the sum of the weights of all indicators within a given layer equals 1.00, and the sum of the weights of all layers also equals 1.00. The weighting scheme used in this study is presented in Table 3. The strategic layer received the highest weight of 0.30, as it is considered central to the successful implementation of the Industry 4.0 concept. The cost and people layers were each weighted at 0.20, as they directly translate strategic intentions into operational reality. The remaining portion of the total weight was distributed across implementation-related processes. Within each layer, processes were further differentiated by their importance, specifically whether they represented critical implementation factors such as the existence of a digital strategy, selection of the digitalisation portfolio, or the management of employees' digital competencies. Critical processes were therefore assigned higher weights based on empirical findings from the model organisation operating in the engineering manufacturing sector.

Table 3. Possible weights for each indicator

	Strategic layer					Cost layer						Personnel layer			Implementation layer				
	The existence of a digital strategy	*Degree of fulfilment of the I4.0 concept*	*Investment estimate*	*Investments in AOP*	*Achieving implementation milestones*	*Portfolio of technical options*	*Portfolio selection*	*Project creation*	*Investment plan*	*ROI in the first year of operation*	*Financial plan*	*Definition of the digital mature worker profile*	*Staff status*	*Qualification level of staff*	*Cooperation with the supplier*	*Purchase price deviation*	*Installation status*	*Test phase action plan*	*Starting the sharp phase*
	KPI I.I.	KPI I.II.	KPI I.III.	KPI I.IV.	KPI I.V.	KPI II.I.	KPI II.II.	KPI II.III.	KPI II.IV.	KPI II.V.	KPI II.VI.	KPI III.I.	KPI III.II.	KPI III.III.	KPI IV.I.	KPI IV.II.	KPI IV.III.	KPI IV.IV.	KPI IV.V.
Weight of indicator	0,5	0,1	0,1	0,2	0,1	0,1	0,2	0,2	0,1	0,2	0,2	0,5	0,25	0,25	0,2	0,2	0,2	0,2	0,2
Σ	1					1						1			1				
Weight of layer	0,3					0,2						0,2			0,3				
Σ	1																		

Source: the authors

Once the weighting framework had been established, the graphical symbols were converted into numerical coefficients, as outlined in Table 1, yielding a structured dataset presented in Table 4. Each coefficient expresses the level of fulfilment of the given indicator within a specific project or process. At this stage, the purpose of the numerical conversion was not to calculate the overall level of digital maturity, but rather to standardise the data for further weighted aggregation and analysis.

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Table 4. Numerical expression of the forces of the relationship

	Strategic layer					Cost layer						Personnel layer			Implementation layer				
	The existence of a digital strategy	*Degree of fulfilment of the I4.0 concept*	*Investment estimate*	*Investments in AOP*	*Achieving implementation milestones*	*Portfolio of technical options*	*Portfolio selection*	*Project creation*	*Investment plan*	*ROI in the first year of operation*	*Financial plan*	*Definition of the digital mature worker profile*	*Staff status*	*Qualification level of staff*	*Cooperation with the supplier*	*Purchase price deviation*	*Installation status*	*Test phase action plan*	*Starting the sharp phase*
Project	KPI I.I.	KPI I.II.	KPI I.III.	KPI I.IV.	KPI I.V.	KPI II.I.	KPI II.II.	KPI II.III.	KPI II.IV.	KPI II.V.	KPI II.VI.	KPI III.I.	KPI III.II.	KPI III.III.	KPI IV.I.	KPI IV.II.	KPI IV.III.	KPI IV.IV.	KPI IV.V.
Factory Monitor	**0**	**0,75**	**1**	**1**	**0,5**	**0**	**0**	**0**	**0**	**0,25**	**0**	**0**	**0,5**	**1**	**0,75**	**1**	**1**	**0,75**	**1**
TrackingApp	**0**	**0,75**	**1**	**1**	**0,75**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**0,5**	**1**	**1**	**1**	**1**	**1**	**1**

Source: the authors, data of the company xyz

Subsequently, each coefficient was multiplied by the corresponding indicator weight (coefficient × weight), ensuring that more significant indicators and processes contribute proportionally more to the final outcome. Summing these weighted scores within each layer produces the weighted layer score, which expresses how well the organisation aligns with the model in that specific area. The maximum achievable score for each layer equals 100 % (coefficient 1.00). Repeating this procedure for all layers and projects enables the identification of well-performing areas and areas requiring improvement. The aggregated results for each layer are summarised in Table 5.

Table 5. Weighted expression of digital maturity in each layer

	Strategic layer					Cost layer						Personnel layer			Implementation layer				
	The existence of a digital strategy	*Degree of fulfilment of the I4.0 concept*	*Investment estimate*	*Investments in AOP*	*Achieving implementation milestones*	*Portfolio of technical options*	*Portfolio selection*	*Project creation*	*Investment plan*	*ROI in the first year of operation*	*Financial plan*	*Definition of the digital mature worker profile*	*Staff status*	*Qualification level of staff*	*Cooperation with the supplier*	*Purchase price deviation*	*Installation status*	*Test phase action plan*	*Starting the sharp phase*
Project	KPI I.I.	KPI I.II.	KPI I.III.	KPI I.IV.	KPI I.V.	KPI II.I.	KPI II.II.	KPI II.III.	KPI II.IV.	KPI II.V.	KPI II.VI.	KPI III.I.	KPI III.II.	KPI III.III.	KPI IV.I.	KPI IV.II.	KPI IV.III.	KPI IV.IV.	KPI IV.V.
Factory Monitor implementation	**0**	**0,075**	**0,1**	**0,1**	**0,05**	**0**	**0**	**0**	**0**	**0,25**	**0**	**0**	**0,13**	**0,25**	**0,15**	**0,2**	**0,2**	**0,15**	**0,2**
Factory Monitor by layers	**42,5%**					**5,0%**						**37,5%**			**90,0%**				
TrackingApp implementation	**0**	**0,075**	**0,1**	**0,2**	**0,075**	**0,1**	**0,2**	**0**	**0**	**0,2**	**0**	**0**	**0,13**	**0,25**	**0,2**	**0,2**	**0,2**	**0,2**	**0,2**
TrackingApp by layers	**45,0%**					**50,0%**						**37,5%**			**100,0%**				

Source: the authors, data of the company xyz

The overall level of digital maturity of the organisation was then determined by aggregating the weighted scores of all layers, using the predefined layer weights. The result represents the weighted overall conformity of the organisation with the digital maturity model, i.e. its quantified level of digital maturity. This allows for a holistic evaluation that integrates all dimensions, i.e., strategic, cost-related, human, and implementation into one composite indicator of organisational readiness for digital transformation. The resulting value, presented in Table 6, expresses the overall fit of the analysed organisation with the reference model in percentage terms.

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Table 6. Resulting digital maturity of the organisation

	Strategic layer					Cost layer						Personnel layer			Implementation layer					
	The existence of a digital strategy	*Degree of fulfilment of the 14.0 concept*	*Investment estimate*	*Investments in AOP*	*Achieving implementation milestones*	*Portfolio of technical options*	*Portfolio selection*	*Project creation*	*Investment plan*	*ROI in the first year of operation*	*Financial plan*	*Definition of the digital mature worker profile*	*Staff status*	*Qualification level of staff*	*Cooperation with the supplier*	*Purchase price deviation*	*Installation status*	*Test phase action plan*	*Starting the sharp phase*	
Project	KPI I.I.	KPI I.II.	KPI I.III.	KPI I.IV.	KPI I.V.	KPI II.I.	KPI II.II.	KPI II.III.	KPI II.IV.	KPI II.V.	KPI II.VI.	KPI III.I.	KPI III.II.	KPI III.III.	KPI IV.I.	KPI IV.II.	KPI IV.III.	KPI IV.IV.	KPI IV.V.	
Factory Monitor implementation by layers	**42,50%**					**5,00%**						**37,50%**			**90,00%**					
Overall weighted digital maturity of the **project**	**12,75%**					**1,00%**						**7,50%**			**27,00%**					**48,25%**
Tracking app implementation by layers	**45,00%**					**50,00%**						**37,50%**			**100,00%**					
Overall weighted digital maturity of the **project**	**13,50%**					**10,00%**						**7,50%**			**30,00%**					**61,00%**
Total weighted digital maturity of the **layer**	**43,79%**					**45,91%**						**37,50%**			**95,26%**					
Overall weighted digital maturity of the **organisation**	**13,14%**					**9,18%**						**7,50%**			**28,58%**					**58,40%**
	0,5	0,1	0,1	0,2	0,1	0,1	0,2	0,2	0,1	0,2	0,2	0,5	0,25	0,25	0,2	0,2	0,2	0,2	0,2	

Source: the authors, data of the company xyz

To complement the numerical results, a network (radar) graph was developed to visualise the mutual alignment of the four key layers of the digital maturity model with the organisation's corresponding activities. The axes of the graph represent the four dimensions of digital maturity, each scaled from 0 to 100 %. The position of each axis point corresponds to the calculated weighted score of the respective layer. A perfectly balanced and digitally mature organisation would be represented by a symmetrical square with axes of equal length, illustrating proportional development across all pillars. Deviations from symmetry reveal imbalances such as stronger strategic capability but weaker financial planning or human resource readiness, which in turn highlight the need for corrective actions. The graphical representation of digital maturity is shown in Figure 1. This visualisation not only summarises the organisation's current maturity level but also provides a diagnostic basis for monitoring progress over time and prioritising strategic initiatives for further improvement.

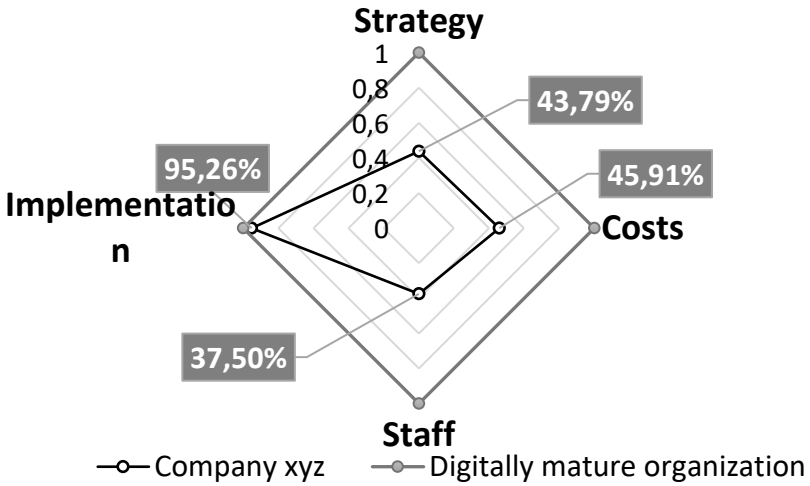


Figure 1. Graphical representation of digital maturity
Source: the authors

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Scaling the level of digital maturity

Building on the quantified weighted correspondence of organisational processes with the general digital maturity model, it becomes possible to express digital maturity as a structured, multi-stage scale. This scaling enables the identification of the organisation's current position on the digital transformation pathway and provides a methodological basis for defining strategic actions required to advance to higher maturity levels. Unlike many traditional models that conceptualise digital maturity as a single, aggregate characteristic of an organisation, the proposed approach recognises its multidimensional nature. By decomposing digital maturity into several analytical layers, strategic, cost, people, and implementation, it allows for a more nuanced evaluation that highlights imbalances and specific areas for targeted improvement. This layer-based scaling thus overcomes the limitations of monolithic maturity assessments that often neglect the contribution of individual subprocesses to overall digital readiness.

In this approach, the scaling process is performed sequentially for each sub-layer of digital maturity, and is visually supported by a network graph that captures the mutual relationships among all four layers. Each stage of the scale is further supplemented by a descriptive narrative, specifying the organisational characteristics and the state of processes corresponding to that maturity level. This detailed categorisation is especially relevant for retrospective model validation or for advanced stages of digital technology implementation, where certain stages of the scale may no longer be fully applicable. The division into distinct layers also facilitates the precise targeting of corrective strategic actions, allowing organisations to focus interventions on those areas that most significantly constrain their advancement in digital maturity.

The proposed scale distinguishes five stages of digital maturity, as presented in Table 7. At the lowest level lies an organisation undergoing digital transformation without a coherent plan or integration with its corporate strategy. In this stage, financial resources, timelines, and staff requirements are undefined, and digital initiatives are implemented in a fragmented or ad hoc manner. In contrast, the highest stage, referred to as the maturity level, represents organisations that have fully institutionalised digital transformation practices. These organisations utilise prior implementation experience, have well-defined investment frameworks, continuously monitor costs and savings, and maintain strong collaboration with technology providers to achieve high efficiency in time and resource utilisation. The intermediate stages of cognition, awareness, and integration reflect the progressive accumulation of knowledge, competencies, and managerial practices that enable structured planning, implementation, and evaluation of digital transformation activities. The maturity stage thus serves as a conceptual benchmark for organisational excellence in digitalisation; for this reason, it is represented not as a percentage band but as a milestone symbolising the ultimate alignment between strategic intent and digital capability.

Table 7. Scaling digital maturity

	0 - 24,99 %	25 - 49,99	50 - 74,99 %	75 - 99,99 %	100%
	PHASE OF IMMATURITY	**INVITATION PHASE**	**AWARENESS PHASE**	**INTEGRATION PHASE**	**MATURITY PHASE**
I. STRATEGY *Digital strategy*	Not defined	It is not aligned with the company-wide strategy	It is partially aligned with the company-wide strategy	It is aligned with the company-wide strategy	It is an integral part of strategic objectives
II. Cost *Investment plan, financial plan*	Costs are not planned in advance	Rough investment estimate	Savings are estimated	Calculating cost savings	Precise planning of investment costs and savings, and regular revision
III. PEOPLE *Profile of a digitally mature employee*	Not defined	Estimate of the number of required employees without defining the profile	The number of required employees and their profile are known	Mapping employee growth against the profile	Motivational system, response to employee needs, knowledge monitoring
IV. IMPLEMENTATION *Collaboration with the supplier on customization, adherence to key milestones, procurement efficiency*	Ad-hoc implementation, zero customization	Ad-hoc implementation, independent milestones outside the company strategy	Planned implementation, motivating milestones, collaboration with the supplier during customization	Gantt chart, milestones, motivation, and customization with the supplier	Effective collaboration with the supplier, adherence to time and costs, regular milestone review

Source: the authors

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Based on the weighted results obtained from assessing the model company, the organisation's overall digital maturity can be classified within this five-level scale. As shown in Table 8, the analysed company (xyz) corresponds to the awareness stage, which indicates that the enterprise has already achieved a basic understanding of the digitalisation concept, implemented specific pilot projects, and established partial procedural structures, yet still exhibits limited integration of these initiatives into its overarching strategic framework. While this level of maturity provides a solid foundation for further digital progress, it also reveals the need for systematic reinforcement of strategic alignment, cost management, and workforce preparedness. However, the classification of overall maturity at this stage does not fully capture the heterogeneity among individual layers of digital maturity, particularly differences in their weighted correspondence to the model and potential imbalances between them.

Table 8. Scaling the overall digital maturity of company xyz

	0 - 24,99 %	25 - 49,99	50 - 74,99 %	75 - 99,99 %	100%
	PHASE OF IMMATURITY	**INVITATION PHASE**	**AWARENESS PHASE**	**INTEGRATION PHASE**	**MATURITY PHASE**
I. STRATEGY *Digital strategy*	Not defined	It is not aligned with the company-wide strategy	It is partially aligned with the company-wide strategy	It is aligned with the company-wide strategy	It is an integral part of strategic objectives
II. Cost *Investment plan, financial plan*	Costs are not planned in advance	Rough investment estimate	Savings are estimated	Calculating cost savings	Precise planning of investment costs and savings, and regular revision
III. PEOPLE *Profile of a digitally mature employee*	Not defined	Estimate of the number of required employees without defining the profile	The number of required employees and their profile are known	Mapping employee growth against the profile	Motivational system, response to employee needs, knowledge monitoring
IV. IMPLEMENTATION *Collaboration with the supplier on customization, adherence to key milestones, procurement efficiency*	Ad-hoc implementation, zero customization	Ad-hoc implementation, independent milestones outside the company strategy	Planned implementation, motivating milestones, collaboration with the supplier during customization	Gantt chart, milestones, motivation, and customization with the supplier	Effective collaboration with the supplier, adherence to time and costs, regular milestone review

Source: the authors

To address this limitation, Table 9 presents a layer-specific scaling of digital maturity, ranking each sub-layer of the model within the same five-level framework. This detailed categorisation complements the network graph (Figure 1) and provides a deeper analytical perspective on the distribution of maturity across dimensions. By identifying which sublayers lag behind and which are more advanced, the model supports the design of targeted strategic interventions. Each maturity stage can thus be associated with key implementation milestones already achieved or to be reached in subsequent phases. These milestones serve as practical reference points for organisations seeking to systematically enhance their digital capabilities, ensuring balanced progress across all layers of the model and a gradual transition toward higher stages of maturity.

Table 9. Scaling the overall digital maturity of company xyz by layers

	0 - 24,99 %	25 - 49,99	50 - 74,99 %	75 - 99,99 %	100%
	PHASE OF IMMATURITY	**INVITATION PHASE**	**AWARENESS PHASE**	**INTEGRATION PHASE**	**MATURITY PHASE**
I. STRATEGY *Digital strategy*	Not defined	It is not aligned with the company-wide strategy	It is partially aligned with the company-wide strategy	It is aligned with the company-wide strategy	It is an integral part of strategic objectives
II. Cost *Investment plan, financial plan*	Costs are not planned in advance	Rough investment estimate	Savings are estimated	Calculating cost savings	Precise planning of investment costs and savings, and regular revision
III. PEOPLE *Profile of a digitally mature employee*	Not defined	Estimate of the number of required employees without defining the profile	The number of required employees and their profile are known	Mapping employee growth against the profile	Motivational system, response to employee needs, knowledge monitoring
IV. IMPLEMENTATION *Collaboration with the supplier on customization, adherence to key milestones, procurement efficiency*	Ad-hoc implementation, zero customization	Ad-hoc implementation, independent milestones outside the company strategy	Planned implementation, motivating milestones, collaboration with the supplier during customization	Gantt chart, milestones, motivation, and customization with the supplier	Effective collaboration with the supplier, adherence to time and costs, regular milestone review

Source: the authors

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Translating the achieved level of digital maturity into corporate strategy

An organisation's knowledge of its achieved level of digital maturity represents a key input for strategic decision-making and for the formulation of corrective actions aimed at enhancing its overall digital capability. The decomposition of digital maturity into four analytical layers, strategic, cost, people, and implementation, enables targeted interventions to be directed precisely toward those organisational areas that exert the strongest influence on the comprehensive maturity outcome. This layered structure enables not only the assessment of the overall state of digital transformation but also the identification of specific dimensions in which imbalances or deficiencies constrain progress.

To visualise these interrelationships, the study introduces the concept of a strategic centre of gravity, reflecting the organisation's current balance across the four maturity layers. This concept enables management to intuitively assess whether the organisation's development is balanced or skewed toward specific areas. The model is based on a two-dimensional coordinate system, where the X-axis represents the implementation and cost layers and the Y-axis represents the people and strategy layers. The origin of the coordinate system marks the ideal equilibrium point corresponding to a fully balanced digital maturity profile. The coordinates of the strategic centre of gravity are calculated as the half-difference between the achieved sub-layer values on each axis, allowing for the determination of its position relative to the origin. This simple yet informative geometric representation makes it possible to visualise deviations from equilibrium and, consequently, to identify directions for future strategic actions.

The interpretation of the centre's position is straightforward. A digitally mature organisation is characterised by a strategic centre of gravity located precisely at the origin of the coordinate system (see Figure 2), signifying a state of proportional development across all four digital maturity layers. Any deviation from this point indicates a structural imbalance: if the centre of gravity lies above the X-axis, the organisation should prioritise strengthening human capital and staff digital competencies; if it is below the X-axis, the focus should shift toward refining its digital strategy and aligning it with corporate objectives. Similarly, a shift to the left of the Y-axis suggests the need to enhance cost-effectiveness and financial planning. In contrast, a displacement to the right indicates excessive emphasis on resource allocation or time scheduling at the expense of flexibility and efficiency.



Figure 2. Strategic focus of a digitally mature organisation
Source: the authors

The analytical logic of this model is further extended in Figure 3, which presents four extreme cases of the strategic centre of gravity's position and illustrates corresponding corrective strategic actions. Each case reflects a different pattern of imbalance between maturity layers and is represented by a bubble, the radius of which indicates the organisation's overall digital maturity level (M, ranging from 0–100 %), while its coordinates (T_x,

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T_γ) define the directional deviation from the equilibrium point. This framework enables an integrated interpretation of both the magnitude and the structural composition of digital maturity.

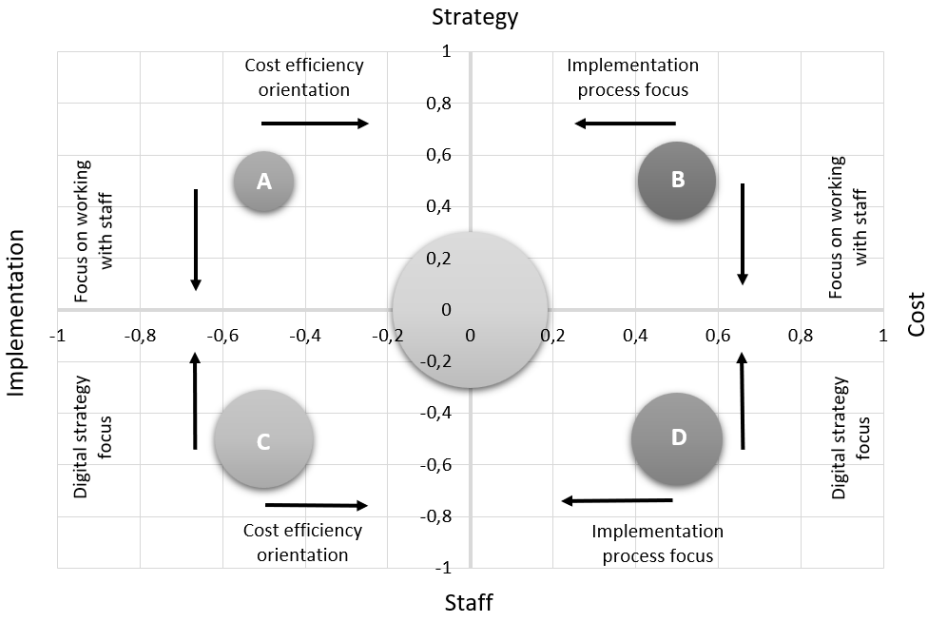


Figure 3. Possible modifications of the strategy according to the position of the centre of gravity
Source: the authors

Optimising corporate strategy based on a digital maturity assessment, however, requires translating analytical findings into specific managerial instruments. One practical approach is to integrate selected key indicators of digital maturity directly into existing strategic management tools, particularly those linked to incentive and performance systems. Such integration ensures systematic monitoring, accountability, and continual revision of digital transformation progress. A suitable framework for this purpose is the Balanced Scorecard (BSC), which organises strategic objectives across four perspectives: financial, customer, internal processes, and learning and growth. Within this structure, the organisation can embed the key indicators of digital maturity into the relevant BSC layers. Relative indicators, those measurable as percentages or ratios, can be directly incorporated as quantifiable performance metrics. Attributive indicators, by contrast, should be defined as binary targets aligned with the BSC's temporal roadmap, typically over an annual horizon. These represent objectives that may not exist at the start of the evaluation period but must be fully implemented by its end. For instance, under a monthly BSC review cycle, the progress of an attributive target could be expected to reach approximately 1/12 (≈8.33 %) of the annual goal each month, whereas under a quarterly cycle, this would equate to 25 % increments. This approach, widely adopted in the engineering and automotive industries, enables attributive objectives to be transformed into measurable proportional goals, thereby ensuring their inclusion in performance evaluation systems.

Building on this analytical framework, the position of the model company's strategic centre of gravity was calculated. In the case of company xyz, the centre is located above the X-axis and significantly to the left of the Y-axis, as shown in Figure 4. This configuration indicates a relatively strong performance in implementation-related activities but a weaker alignment in the cost dimension.

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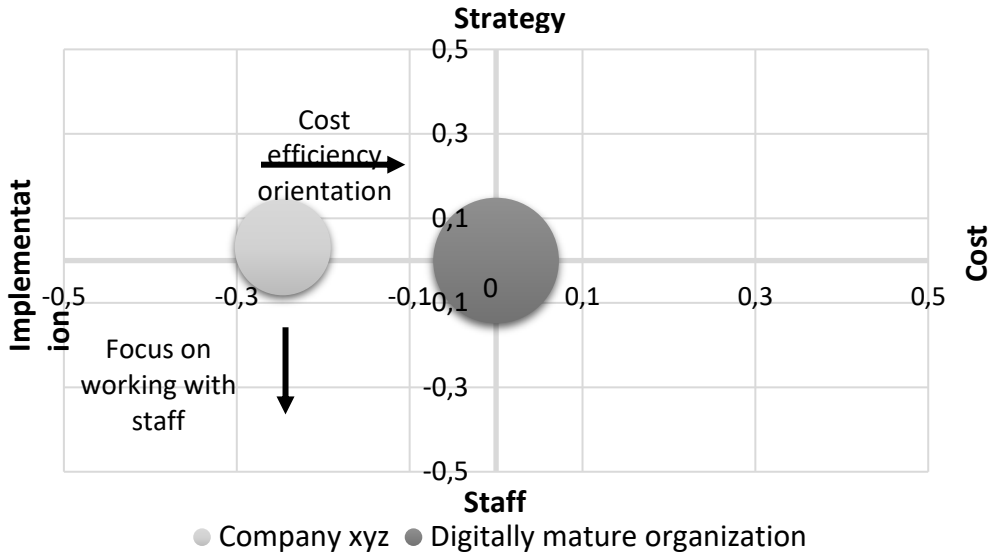


Figure 4. Strategic focus of digital maturity of company xyz
Source: the authors

The combination of the centre of gravity's location and the radius of the bubble representing total maturity thus provides a comprehensive diagnostic perspective. It enables the interpretation of both the organisation's current phase of digital transformation and the proportionality of its internal development. Two assumptions underlie this interpretation. First, a digitally mature organisation maintains its strategic centre of gravity at or near the coordinate origin, implying balanced advancement across all maturity layers. This condition need not correspond to the highest absolute level of digital maturity but rather to a harmonious implementation trajectory in which each layer evolves in tandem. Second, the bubble's radius reflects the organisation's overall maturity magnitude; the closer it approaches 100 %, the higher the level of conformity with the reference model. Deviations from symmetry or from the coordinate origin, therefore, signal areas that require strategic realignment before advancing to the next stage of the maturity scale.

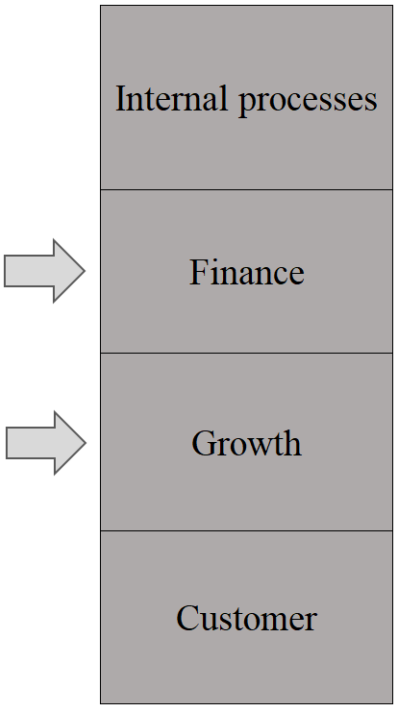
Consequently, the analysis suggests specific corrective strategic measures for the model company. The leftward displacement of the strategic centre of gravity indicates an imbalance between the implementation and cost layers, with the latter achieving a lower weighted fit to the digital maturity model. To restore equilibrium before progressing to the next stage, the organisation should prioritise cost-efficiency improvement and financial planning within its Industry 4.0 implementation projects. Simultaneously, the upward shift above the X-axis highlights a need for stronger emphasis on human resource development, particularly in enhancing employees' digital literacy and skills. While this imbalance poses a lesser risk than the cost-related one, addressing both ensures a smoother transition to higher maturity stages.

Integrating these insights into the organisation's strategic tools is essential for ensuring long-term alignment between digital transformation initiatives and business strategy. The projection of the key indicators defining the weaker cost and HR layers into the Balanced Scorecard framework is presented in Table 10, which summarises potential strategic adjustments aimed at restoring balance and promoting consistent digital growth across all layers of maturity.

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Table 10. Possible adjustments to the corporate strategy

	Indicator		Verifying of compliance
I. Strategy	KPI I.I.	The existence of a digital strategy	*attributively*
	KPI I.II.	Degree of fulfilment of the I4.0 concept	*proportionally*
	KPI I.III.	Investment estimate	*attributively*
	KPI I.IV.	Investments in AOP	*attributively*
	KPI I.V.	Achieving implementation milestones	*proportionally*
II. Cost	KPI II.I.	Portfolio of technical options	*attributively*
	KPI II.II.	Portfolio selection	*attributively*
	KPI II.III.	Project creation	*attributively*
	KPI II.IV.	Investment plan	*attributively*
	KPI II.V.	ROI in the first year of operation	*proportionally*
	KPI II.VI.	Financial plan	*attributively*
III. Personnel	KPI III.I.	Definition of the digital mature worker profile	*attributively*
	KPI III.II.	Staff status	*proportionally*
	KPI III.III.	Qualification level of staff	*proportionally*
IV. Implementation	KPI IV.I.	Cooperation with the supplier	*proportionally*
	KPI IV.II.	Purchase price deviation	*proportionally*
	KPI IV.III.	Installation status	*proportionally*
	KPI IV.IV.	Test phase action plan	*proportionally*
	KPI IV.V.	Starting the sharp phase	*attributively*



Source: the authors

The findings of this study are consistent with the results of previous research on digital transformation in industrial enterprises. In accordance with Elafri et al. (2022), the absence or insufficient quality of an organisation's digital strategy has been confirmed as a key barrier to digital transformation, negatively affecting a wide range of subsequent implementation activities. These findings are consistent with recent studies that emphasise the interdependence of strategic alignment, workforce readiness, and cost governance as key determinants of successful digital transformation in industrial enterprises (Mihajlovic et al., 2025; Ecer et al., 2024). The analysis further supports the conclusion of Raj et. al. (2020) that workforce capabilities, specifically employees' digital literacy and readiness to adapt, constitute a critical determinant of successful implementation. These results are reflected in the present study's outcomes, where the weakest layers of digital maturity were identified in the strategic, cost, and personnel dimensions, while the implementation dimension showed relatively higher alignment with the general digital maturity model.

From a methodological perspective, this research contributes to the literature by introducing a systematic verification procedure that quantifies the alignment between organisational processes and the key indicators of a digital maturity model. The proposed method combines a weighted matrix analysis with a rigorous structure of attributive and relative indicators, thereby enabling a reproducible and objectively comparable measurement framework. This approach contrasts with the more common self-assessment models, which often rely on subjective perception rather than verifiable internal data. The introduction of the concept of a strategic centre of gravity represents an additional methodological contribution, as it allows the organisation to visualise and interpret imbalances between the sub-layers of digital maturity and to formulate targeted strategic actions accordingly.

The results also provide a practical framework for managers seeking to align digital transformation with corporate strategy. The model enables organisations to identify critical weaknesses, quantify their maturity level across individual layers, and prioritise interventions that have the highest expected impact on digital performance. Embedding the identified indicators into the Balanced Scorecard system ensures that digitalisation metrics become integral components of strategic management, performance evaluation, and continuous improvement. In this way, digital maturity ceases to be a static diagnostic and becomes a dynamic managerial instrument.

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Despite the coherence of the findings, several limitations must be acknowledged. The study relies on data from a single manufacturing enterprise in the engineering sector, which constrains the statistical generalisability of the results. Additionally, while the weighting of indicators was informed by expert judgment and literature review, the model's calibration may differ across industries or organisational sizes. Therefore, future research should validate the model across a broader range of enterprises and sectors, apply longitudinal observation to track digital maturity progression over time, and assess how the interaction between layers influences overall strategic performance. Expanding the model beyond the engineering industry could further confirm its transferability and strengthen its practical applicability in diverse industrial contexts. In summary, the study demonstrates that the absence of a digital strategy, insufficient cost control, and a lack of digitally skilled personnel continue to be the primary obstacles to achieving higher levels of digital maturity. The proposed methodological framework offers both researchers and practitioners a structured, verifiable, and analytically transparent approach to diagnosing these deficiencies and guiding strategic responses.

Conclusions

The primary aim of this paper was to develop and apply a systematic framework for determining the digital maturity of enterprises operating in the engineering sector. Drawing upon existing literature, assessment frameworks, and practical insights from the case organisation, an analytical-synthetic procedure was employed to construct a digital maturity model reflecting the specific conditions of industrial production, including its links to the LEAN methodology. A distinctive feature of the model is its division into four sub-layers: strategic, cost, personnel, and implementation, which allows for the evaluation of both comprehensive and partial digital maturity levels. The model was operationalised through a defined set of key compliance indicators, categorised into attributive and relative indicators according to their measurability. Internal company data from a representative engineering enterprise (Company XYZ) was used to validate the model, distinguishing this approach from previous studies that typically rely on questionnaire-based self-assessments. The evaluation of compliance was performed using weighted matrix analysis, which provided both layer-specific and aggregate insights into digital maturity performance.

Furthermore, by introducing the strategic centre of gravity framework, the study linked the diagnostic phase directly to strategic management. The approach enables organisations to identify the layers in which maturity gaps are most pronounced and to implement corrective measures through existing strategic tools, most notably the Balanced Scorecard, into which the sub-indicators can be directly integrated. This integration ensures continuous monitoring, ownership, and accountability for digital transformation initiatives across the organisation.

The authors recognise certain limitations, particularly the reliance on proprietary internal data, which constrains the replicability of the study. Nonetheless, this limitation also represents a strength, as it demonstrates the practical applicability of the model in real business environments without depending on self-reported data. The proposed approach thus contributes to both theory and practice, advancing the measurement of digital maturity through quantifiable, data-driven methods and providing a decision-support tool for aligning digital initiatives with corporate strategy. The newly introduced approach to assessing digital maturity and linking it with strategic planning constitutes a significant step towards the effective utilisation of digital technologies and processes in industrial enterprises. The model provides researchers with a reproducible methodological framework, while offering managers and practitioners a concrete instrument for identifying, quantifying, and addressing maturity gaps. Consequently, this study delivers a valuable contribution to both the academic understanding and the practical management of digital transformation in the engineering sector.

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MANUFACTURER-USER COLLABORATIVE INNOVATION VIA E-COMMERCE PLATFORMS*

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Abstract. This study examines how e-commerce ecosystems reconfigure manufacturer-user (MU) collaborative innovation networks, drawing on evidence from China's fashion and apparel industry. Through a qualitative multi-case analysis of two platform-mediated collaborations—modular knitwear co-creation and sustainable denim development—we identify that e-commerce platforms act as proactive architects of innovation. They enable role fluidity among problem setters, solvers, and reviewers; facilitate hybridisation of collaboration modes (e.g., resource transfer with strategic alliances); and institutionalise digital, knowledge, and organisational mechanisms that reduce information asymmetry and accelerate iteration. The paper presents an integrated framework that bridges service-dominant logic, user innovation theory, and platform ecosystem perspectives, providing practical insights for managers and platform designers on structuring effective, trust-based co-innovation in digital environments.

Keywords: Manufacturer-user collaborative innovation; E-commerce ecosystems; Fashion industry; Platform intermediation; Value co-creation

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1. Introduction and Review of Literature

In an era of accelerating digital transformation, firms increasingly assume multiple, evolving roles: they define market needs, develop and validate technologies, translate scientific discoveries into commercial offerings, evaluate market applications, and co-construct future industry trajectories. High-quality innovation, particularly inter-firm collaborative innovation, has become a central driver of sectoral linkages and innovation-led growth in this new stage of development. While existing research has extensively examined collaborative technological innovation within industrial chains and regional clusters, it has largely overlooked the heterogeneity across firm types—especially the distinctive and increasingly influential role of users. Traditionally, manufacturers have dominated innovation studies; yet users are far more than passive buyers. They are active participants whose market positions, technical demands, and contextual knowledge increasingly shape innovation processes and outcomes.

The influence of users in product and technological development now extends well beyond transactional purchasing. Empirical evidence indicates that when manufacturers systematically integrate user feedback into new product development, innovation performance improves significantly. Downstream lead users—armed

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with substantial bargaining power and stringent technical requirements for intermediate goods—often catalyse upstream technological advances (Vanleene et al., 2017). Compared to ordinary manufacturers, end users or final assemblers frequently operate on a larger scale and possess stronger capacities to steer innovation across entire industry chains. Consequently, a growing number of firms are adopting collaborative innovation strategies to share knowledge, access complementary resources, and accelerate capability building. Within this collaborative paradigm, lead users-those with forward-looking needs and strong incentives to secure early-mover advantages-have gained particular salience. These users often initiate innovation activities when existing products fail to meet their advanced requirements and actively seek partnerships with manufacturers to co-create solutions (Tekic & Willoughby, 2019).

As innovation logic increasingly shifts toward post-Schumpeterian perspectives—where demand-side factors and real-world usage contexts drive technological trajectories—there is a pressing need to broaden scholarly attention to user-led innovation paradigms and the specific mechanisms underpinning MU collaboration. This paradigm shift is substantiated by a growing body of empirical research that delineates the multifaceted roles users play in co-development processes. For instance, Dean, Zhang and Xiao (2024) elucidate how customer involvement in co-development enhances problem-solving efficacy and decision-making quality during new product development (NPD), particularly through iterative feedback loops that bridge experiential user knowledge with technical feasibility. Similarly, Sabatini, Pascucci and Gregori (2023) provide empirical evidence from the smart product sector, demonstrating that deep customer involvement in technological development not only refines product functionality but also accelerates market adoption by ensuring alignment with latent user needs. These studies underscore that users are not merely passive recipients but active co-developers whose contextual insights are critical for reducing developmental uncertainties and enhancing product-market fit.

Extending this perspective, recent research further unpacks the contingent nature and performance implications of user involvement. Zaefarian et al. (2025) systematically examine when and how customer involvement as a co-developer translates into superior supplier NPD performance, highlighting the mediating roles of knowledge integration and relational governance. Their findings suggest that the benefits of co-development are maximised when involvement is structured around clear intellectual property frameworks and aligned incentives—an insight particularly relevant for platform-mediated ecosystems. Complementarily, Lu, Zou, and Du (2024) investigate the differential impacts of two forms of customer involvement (information provision versus co-development) across various NPD stages within digital contexts. They find that co-developing yields greater performance benefits in later stages, such as testing and launch, where real-world usage feedback is paramount. This staged approach to involvement aligns with the lead user theory advanced by de Jong et al. (2024), who conceptualise lead users as a vital source of Schumpeterian opportunities in industrial product development. Their work posits that lead users, by articulating advanced needs and pioneering solutions, effectively de-risk radical innovation and chart new technological trajectories, thereby embodying the core of post-Schumpeterian innovation dynamics.

Beyond functional and commercial outcomes, the user-led paradigm is increasingly linked to strategic initiatives such as sustainability and systemic innovation. Reppmann et al. (2025) investigate how involving customers in corporate sustainability initiatives can "activate" sustainable consumption behaviours, thereby creating a virtuous cycle where user feedback directly informs eco-innovation. This aligns with the growing emphasis on sustainable co-creation observed in platform ecosystems. Furthermore, Marty and Ageron (2024) propose a conceptual framework for directly connecting customers to the supply chain, arguing that such integration enhances transparency, responsiveness, and value co-creation across the network—a notion central to understanding MU collaboration in digitally linked value chains. The collaborative ethos extends to the creative industries as well, where Bujor, Avasilcai and Avram (2024) document, through case studies, how co-innovation with users fosters novelty and cultural resonance.

Meanwhile, the digital infrastructure enabling these collaborations is scrutinised by Rohit, Ranjan and Shainesh (2025) in their meta-analysis of service marketing mix and customer engagement, and by Gupta and Khan (2024) in their systematic review of artificial intelligence's role in facilitating personalised and scalable customer engagement for co-creation. These digital enablers are critical for managing the complexity of multi-actor

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collaboration, as noted by Sonta-Draczkowska et al. (2025) in their systematic literature review, which identifies project management challenges and solutions in user co-creation initiatives. Finally, the motivational and experiential dimensions are addressed by Kieling and Boeing (2025), who find that product co-creation can positively influence consumer hedonic adaptation, thereby enhancing long-term engagement and satisfaction. Collectively, this literature substantiates a comprehensive view of user-led innovation as a multi-mechanism, context-dependent process that is fundamentally reshaping collaboration paradigms, setting the stage for our investigation into its reconfiguration within e-commerce ecosystems.

The manufacturer-user (MU) collaborative innovation process is inherently characterised by high uncertainty and information asymmetry. Knowledge regarding product usage, contextual requirements, and emergent needs predominantly resides with users, while solution expertise, technical know-how, and production capabilities are concentrated among manufacturers. This division of knowledge creates both barriers and opportunities: lead users can act as critical brokers of demand-side insights and strategic partners in co-development, yet misaligned incentives and imperfect information flows can impede effective collaboration. Notwithstanding the rising strategic importance of MU collaborative innovation, two critical research gaps persist. First, the literature provides a limited understanding of user-led collaborative innovation, particularly in terms of how lead users initiate, shape, and sustain co-innovation processes with manufacturers. Second, comprehensive theoretical frameworks that integrate firm-type heterogeneity, information asymmetry, and multi-stakeholder coordination within digitally-mediated industry ecosystems remain underdeveloped. These gaps are especially salient in platform-driven contexts, such as e-commerce ecosystems, where digital intermediaries, data-rich interactions, and rapid feedback loops fundamentally reshape the relationships between manufacturer
s and users.

To address the indicated gaps, this study examines the following research question: **How do e-commerce ecosystems reconfigure the structure and dynamics of manufacturer-user (MU) collaborative innovation networks?**

We examine this question empirically within the fashion and apparel industry-a sector that vividly exemplifies MU co-innovation. Here, lead retailers, brands, and large buyers exert significant influence on upstream suppliers' technology adoption, design standards, and production processes. Consumers and trend-setting users provide rapid, granular signals about preferences and usage contexts, while e-commerce platforms actively mediate interactions, data flows, and market-testing mechanisms. By exploring MU collaboration in this setting, the paper seeks to (1) theorise how lead users and manufacturers co-create innovation under conditions of information asymmetry and platform mediation, (2) identify the mechanisms through which user knowledge is integrated into technical problem-solving and product development, and (3) evaluate the implications for firm-level innovation capabilities and industry-wide innovation diffusion.

The contributions of this paper are threefold. Empirically, it introduces a user-centric perspective into the study of collaborative innovation within digital commerce ecosystems, an area traditionally dominated by manufacturer-focused accounts. Theoretically, it develops an integrated framework for understanding MU collaborative innovation that foregrounds firm-type heterogeneity, knowledge complementarities, and platform-enabled coordination mechanisms. Practically, the findings offer actionable guidance for managers and platform designers on structuring collaborations that effectively harness lead-user insights while aligning incentives and mitigating informational frictions. Collectively, these advances aim to deepen our understanding of how manufacturer-user partnerships can drive high-quality innovation and reshape industry trajectories in the digital age.

2. Conceptual Basis

The conceptualisation of manufacturer-user (MU) collaborative innovation within e-commerce ecosystems lies at the intersection of service-dominant logic, value co-creation theory, and the digital transformation enabled by platform technologies. This integrative perspective is essential for understanding how e-commerce

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ecosystems reconfigure traditional innovation networks, shifting them from manufacturer-centric, linear processes to dynamic, user-driven value co-creation systems.

Service-Dominant Logic and Value Co-Creation in Innovation

The Service-Dominant (SDL) logic framework, pioneered by Vargo and Lusch (2004, 2008a, 2008b, 2016), provides a robust theoretical foundation for understanding MU collaborative innovation. SDL reconceptualises value creation as the result of resource integration among multiple actors within a service ecosystem. In this view, all economies are service economies, and goods—including innovative products—are merely vehicles for service provision. Applied to innovation contexts, this means that manufacturers, users, platform intermediaries, and technologies all act as resource integrators, each contributing unique knowledge, capabilities, or contextual insights to the innovation process (Vargo & Lusch, 2016). Value co-creation becomes the operational mechanism through which this resource integration is enacted. Unlike traditional innovation models, where value is created by manufacturers and consumed by users, value co-creation emphasises collaborative processes in which both manufacturers and users jointly generate innovative outcomes (Saunila, Ukko & Rantala, 2019; Fonferek, Kleinaltenkamp & Möller, 2019). This paradigm shift is particularly salient in e-commerce ecosystems, where digital platforms facilitate continuous interaction and knowledge exchange between manufacturers and users, enabling real-time resource integration and iterative solution development.

The Evolution of Innovation Paradigms: From Producer-Led to User-Driven Collaboration

The theoretical understanding of innovation has evolved significantly through several distinct paradigms. The Schumpeterian perspective initially emphasised the entrepreneurial spirit (Mark I) and later large firms (Mark II) as primary innovation drivers, focusing predominantly on manufacturer-led, internally confined processes. The Neo-Schumpeterian paradigm expanded this view to include social institutions through concepts such as the "National Innovation System" (Freeman, 1987) and the "Triple Helix" model (Etzkowitz & Leydesdorff, 1995), which highlighted the importance of university-industry-government collaborations. While broadening the scope of innovation beyond individual manufacturers, this paradigm remained predominantly macro-level and manufacturer-centric. The emergence of the Post-Schumpeterian paradigm, significantly advanced by von Hippel's user innovation theory (1986, 2017), marked a fundamental shift in the understanding of innovation. Von Hippel (2017) demonstrated that users—both individuals and firms—frequently innovate to address their specific needs, often without assistance from manufacturers. This theoretical development expanded the boundaries of innovation beyond manufacturers as sole sources to propose user-driven innovation paradigms. Hippel (2017) further argued for a paradigm shift from individual manufacturer innovation to user-driven and open collaborative innovation, providing crucial theoretical grounding for MU collaborative innovation theory. Within this evolving landscape, three distinct innovation models coexist: manufacturer-alone innovation, user-alone innovation, and manufacturer–user collaborative innovation. While manufacturer innovation typically leverages economies of scale and focuses on value capture through intellectual property, user innovation is fundamentally demand-driven, often resulting in "free innovation" that prioritises use value over proprietary control (von Hippel, 2017). MU collaborative innovation represents a hybrid approach that simultaneously leverages the distinct knowledge sets of both manufacturers and users, leading to joint value creation through structured collaboration.

E-commerce Ecosystems as an Inflexion Point for MU Collaboration

Digitalisation has already transformed the boundaries and complexity of innovation networks. Technologies such as big data analytics, digital prototyping tools, and communication platforms have enabled greater user participation, real-time feedback, and decentralised innovation activities (Lember Brandsen & Tõnurist, 2019; Chen et al., 2021). However, e-commerce ecosystems represent a qualitative leap within this digital transformation. Unlike prior technologies that primarily facilitated discrete interactions, e-commerce platforms possess capabilities in data aggregation, matchmaking, and ecosystem orchestration, enabling them to act as active architects of innovation networks. E-commerce platforms transform MU collaboration through several unique capabilities. They aggregate diverse user needs and preferences at unprecedented scale, enabling manufacturers to identify emerging trends and innovation opportunities. They provide digital toolkits that lower barriers to user participation in design and customisation. They facilitate rapid prototyping and market testing through integrated feedback mechanisms. Most importantly, they reconfigure innovation networks from

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sequential, manufacturer-driven processes to dynamic, multi-directional value co-creation ecosystems where users transition from passive recipients to active co-designers, quality assessors, and innovation drivers.

These transformative potential positions e-commerce ecosystems not merely as transactional platforms but as new structural conditions for MU collaborative innovation in the digital age. By synthesising these three conceptual streams—service-dominant logic, the evolution of innovation paradigms, and the transformative role of e-commerce ecosystems—this research establishes a foundation for investigating how digital platforms reconfigure the structure and dynamics of manufacturer-user collaborative innovation networks.

3. Methodology

To investigate how e-commerce ecosystems reconfigure the structure and dynamics of manufacturer-user (MU) collaborative innovation networks, we employed a qualitative multi-method research design, which is well-suited for theory building in complex, emerging contexts (Yin, 2016). A multi-method approach enables data triangulation and provides rich, contextual insights into the mechanisms and processes underpinning platform-mediated innovation. Our study focuses on the fashion and apparel industry within leading Chinese e-commerce ecosystems, a context where digital platform mediation, fast-changing consumer preferences, and intense competition make MU collaborative innovation particularly salient.

3.1 Research Design and Case Selection

We adopted a multiple-case study design to capture the heterogeneity and complexity of MU collaborative innovation across different platform contexts. Multiple cases allow for comparative analysis and enhance the theoretical generalizability of emerging patterns (Eisenhardt & Graebner, 2007). Case selection followed a theoretical sampling logic, aiming to maximise variation in platform types, firm sizes, and collaboration models while ensuring relevance to the research question (Yin, 2016). We selected two in-depth cases that represent distinct yet complementary models of MU collaborative innovation within Chinese e-commerce ecosystems:

Case A: Co-creation with Micro-Influencers and Fast-Fashion Retailers. This case examines a vertically integrated OEM (anonymised as "Shandong Knit Co.") that collaborated with a leading fast-fashion retailer ("BuyFast") and micro-influencer communities on Xiaohongshu to co-create a line of modular knitwear. This case exemplifies user-led ideation and platform-facilitated, on-demand production.

Case B: Platform-Analytics-Driven Sustainable Line Development. This case focuses on a large online-native brand ("BrandX") that leveraged Tmall's co-creation tools, platform analytics, and livestreamer co-design sessions to develop a new sustainable denim line in partnership with an upstream fabric mill and several lead retailers. This case illustrates data-driven, platform-orchestrated collaboration across the value chain.

Together, these cases cover a spectrum from socially driven (Xiaohongshu) to transactionally oriented (Tmall) platforms, and from product-level customisation to strategic sustainable innovation, offering a robust basis for analysing the reconfiguration of MU innovation networks.

3.2 Data Collection

We conducted intensive fieldwork between April and September 2024, employing a multi-method data collection strategy to ensure triangulation and depth. Our data corpus combines platform data, semi-structured interviews, and archival documents, as detailed in Table 1.

Table 1. Data Collection Overview

Data Source	Details and Period
Semi-structured Interviews	28 interviews (mean length: 60 minutes) with respondents from across the e-commerce ecosystem, including 6 Brand/Manufacturer representatives, 5 Platform managers, 7 Lead Users/Retailers, 6 Independent Designers/Micro-brands, and 4 Technology/Logistics providers.
Platform Data	Aggregated, anonymised datasets (2019-2024) from Tmall and Taobao (via official APIs), public user-generated content from Xiaohongshu, and selected livestreaming campaign records. Analysed metrics included search trends, SKU launch cadence, review sentiment, and co-design participation rates.
Archival Data	Internal firm documents from case companies, platform white papers (e.g., Tmall Trend Insights Report), annual reports, patent/licensing disclosures, and media coverage of collaborative initiatives (2018-2024).

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A total of 28 semi-structured interviews were conducted with a diverse range of stakeholders across the e-commerce ecosystem, ensuring insights from platform orchestrators, innovation leaders, and implementation partners.

The interviewees included:
Brand and Manufacturer Representatives (6 persons): Including R&D leads, product managers from heritage manufacturers, and fast-fashion OEMs involved in co-creation projects;
Platform Management (5 persons): Including product managers from Tmall Innovation Centre and community operation leads from Xiaohongshu;
Lead Users and Retailers (7 persons): Including product development managers from large omni-channel retailers, buying group representatives, and merchandising specialists;
Independent Designers and Micro-Brands (6 persons): Key figures in platform-led co-design initiatives;
Logistics and Technology Providers (4): Offering perspectives on supply chain integration and digital tooling that enable rapid iteration.

This composition allowed us to triangulate data between platform architects, manufacturing innovators, and user representatives, capturing a holistic view of MU collaborative innovation dynamics.

3.3 Data Analysis

To systematise the analysis across multiple data sources and cases, we applied a hybrid approach of deductive and inductive thematic analysis, supported by the grounded theory technique of constant comparison (Charmaz, 2006). The study was facilitated by NVivo software for data management, coding, and memoing.

The analysis unfolded through three iterative stages:
Initial Coding: We began with open coding of interview transcripts and key sections of archival documents. First-order codes captured in-vivo terms and specific actions described by participants (e.g., "real-time trend spotting," "co-design livestreams," "modular component sharing").

Theme Development: Through constant comparison within and across cases, we grouped first-order codes into second-order themes. This stage involved identifying recurring patterns related to how platforms alter information flows, redefine participant roles, create new collaboration modes, and introduce new coordination mechanisms.

Aggregate Dimension Integration: Finally, we abstracted the second-order themes into aggregate dimensions that constitute the core mechanisms through which e-commerce ecosystems reconfigure MU innovation networks. This process resulted in the identification of the framework presented in the Findings section.

This rigorous, iterative process ensured that the resulting conceptual model was deeply grounded in empirical evidence while being sufficiently abstract to offer theoretical contributions.

4. Case Introduction: Collaborative Innovation in E-commerce Fashion Ecosystems

China's fashion and apparel industry is undergoing a profound digital transformation, with e-commerce ecosystems emerging as pivotal forces in reconstructing manufacturer-user (MU) collaborative innovation networks. This evolution shifts the focus from manufacturer-centric, sequential development processes to platform-mediated, user-integrated co-creation pathways. The following two cases from leading Chinese e-commerce platforms exemplify this paradigm shift, demonstrating how digital ecosystems enable more responsive, efficient, and consumer-centred innovation models.

4.1 Case A: Modular Knitwear Co-creation (Shandong Knit Co. × BuyFast × Xiaohongshu)

Background and Context

Shandong Knit Co. represents a medium-sized original equipment manufacturer (OEM) with advanced 3D knitting capabilities, historically focused on producing standardised lines for domestic fast-fashion brands. BuyFast operates as a national fast-fashion retailer with a dominant e-commerce presence and substantial

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category buying power. The collaboration integrated Xiaohongshu micro-influencer communities, known for pioneering modular fashion styling trends.

Problem Setting: Identifying Innovation Opportunities
The collaborative initiative emerged from the convergence of challenges and opportunities. BuyFast identified persistent operational inefficiencies, including rapid churn of knitwear trends and elevated return rates (approaching 25%), primarily attributable to fit inaccuracies and personalisation gaps. Concurrently, Xiaohongshu platform analytics detected a surge in consumer interest in "modular" and "multi-way" knitwear configurations among fashion-forward demographics. This convergence prompted BuyFast to articulate a strategic innovation challenge: developing a knitwear line that enabled extensive personalisation while minimising inventory risk and maintaining viable profit margins.

Collaborative Process and Mode
The partnership adopted a hybrid Resource Transfer and Strategic Alliance model. BuyFast formally commissioned Shandong Knit Co. for a co-design pilot program leveraging 3D knitting technology. Xiaohongshu micro-influencers participated as lead users, contributing to the modular configuration definitions—including removable collars, variable sleeve lengths, and interchangeable patch elements—while providing crucial validation of the prototypes. Tmall's platform analytics and BuyFast's sales volume guarantee financially underwrote initial small-batch production runs, mitigating manufacturing risk.

Problem Solving and Technical Implementation
Shandong Knit Co. deployed integrated digital toolkits—including 3D patterning software and virtual fit simulation—that directly connected with platform feedback mechanisms, enabling rapid design iterations. Technical adjustments focused on optimising stitch gauge, selecting yarn blends, and engineering modular connectors. Micro-influencers provided detailed fit documentation through video content and suggested practical use cases for modular components, directly influencing the design of connectors and the development of fastening systems.

Review and Validation Mechanisms
The innovation process incorporated multi-stage validation through platform-enabled mechanisms. Initial product releases utilised livestreamed pre-sales campaigns, which generated real-time consumer response metrics. Platform data—including add-to-cart rates, conversion performance during livestream events, and detailed analysis of return reasons—enabled continuous refinement throughout the product lifecycle. This integrated approach significantly compressed design-to-market timelines, reducing traditional 12-week cycles to 4–6 weeks for pilot SKUs.

Documented Outcomes and Performance Impact
The modular knitwear pilot demonstrated significant performance improvements across multiple dimensions. Pilot SKUs achieved a 20% higher conversion rate and 35% reduction in return rates compared to conventional knitwear lines. Manufacturer margins improved substantively through reduced overstock liabilities and premium pricing enabled by customisation capabilities. The collaboration established a new operational paradigm for responsive, demand-driven production within fast-fashion ecosystems.

4.2 Case B: Sustainable Denim Co-creation (BrandX × Fabric Mill × Tmall)

Background and Context
BrandX operates as an online-native fashion brand, targeting environmentally conscious consumers, and faces increasing market pressure to accelerate the adoption of sustainable practices. MillY represents an innovative fabric manufacturer that possesses novel low-water indigo finishing technology but lacks established market channels for technology commercialisation. Tmall's co-creation campaign infrastructure provided the technological platform connecting brands, suppliers, and consumer panels.

Problem Setting: Defining Sustainability Parameters
The collaboration addressed dual challenges: BrandX required commercially viable, sustainable denim that maintained traditional indigo aesthetic qualities while substantially reducing water and chemical utilisation.

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MillY sought strategic partnerships to scale its proprietary technology beyond laboratory implementation. Platform analytics have identified a growing consumer segment that prioritises verifiable sustainability credentials in their fashion purchasing decisions.

Collaborative Process and Mode
The partnership established a hybrid model combining Technical Patent Cooperation and R&D Outsourcing. BrandX convened a specialised consumer panel—comprising eco-influencers and sustainability-focused lead users—through Tmall and Xiaohongshu integration to establish acceptability thresholds for colourfastness, hand feel, and price sensitivity. MillY contributed process intellectual property and co-developed finishing recipes with BrandX's design team through joint laboratory sessions.

Problem Solving and Technical Development
Collaborative R&D incorporated iterative pilot batches, laboratory performance testing, and consumer blind wear trials. Intellectual property arrangements were negotiated proactively, resulting in joint patent filings for process modifications and structured revenue-sharing agreements for future technology licensing. This formal governance framework enabled open knowledge exchange while protecting the interests of participants.

Review and Validation Mechanisms
Tmall's ecosystem enabled phased product validation through exclusive early access for panel members, followed by livestreamed production documentation sessions that transparently communicated manufacturing provenance and laboratory performance metrics. User-generated content, structured wear-test feedback, and detailed return analysis created continuous feedback loops that informed ongoing process optimisation and product refinement.

Documented Outcomes and Performance Impact
The sustainable denim line achieved substantial market and environmental impact. Products commanded premium pricing (15-20% above conventional alternatives) while reducing water consumption per garment by 60% compared to BrandX's previous denim lines. The collaboration generated secondary licensing interest from two regional brands, demonstrating the commercial viability of the underlying technology. Consumer response metrics indicated particularly strong conversion performance among environmentally conscious demographic segments, validating the platform-mediated sustainability positioning.

5. MU Collaborative innovation

5.1. MU Collaborative Roles

The analysis of the two cases reveals that at the core of manufacturer-user (MU) collaborative innovation within e-commerce ecosystems lies a dynamic and often fluid interplay of three distinct roles: the Problem Setter, the Problem Solver, and the Reviewer. The assignment of these roles is not fixed; instead, actors shift between them depending on the context and stage of the innovation process, a pattern clearly evidenced in our field data.

The Problem Setter is the entity that identifies and articulates the initial need or challenge, thereby framing the innovation agenda. Contrary to traditional innovation models, our findings underscore that users frequently initiate this process. In Case A, the fast-fashion retailer BuyFast identified operational pain points, including high return rates and the inability to keep pace with rapidly changing trends. Concurrently, micro-influencer communities on Xiaohongshu detected and amplified emerging consumer interest in modular apparel. As one platform product manager from Tmall noted, "The most valuable innovation signals often come directly from the users' side. Our analytics can quantify a trend, but it's the users who first give it a name and a concrete form." This convergence of user-articulated problems ensured the subsequent collaboration was precisely targeted at genuine market gaps.

Following the problem definition, the Problem Solver role emerges, entailing the development of technical solutions. While manufacturers like Shandong Knit Co. (Case A) and the fabric mill MillY (Case B) brought essential R&D infrastructure and production expertise to this role, users were far from passive. In Case A,

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micro-influencers actively co-designed modular components, providing specific inputs on connectors and fastenings. A lead designer from a micro-brand involved in similar initiatives explained, "We're not just giving a brief. We are in the digital room with the manufacturers, manipulating 3D models together. Our practical sense of what works on a body directly changes the technical parameters." This iterative, co-design approach, supported by digital toolkits, ensured that solutions were both technically sound and user-validated.

Finally, the Reviewer role is critical for evaluating and validating solutions through real-world application and testing. Users are the primary actors in this role, and their feedback, mediated by platform mechanisms, creates rapid iteration loops. In Case A, real-time metrics from livestreamed pre-sales and detailed return analysis served as continuous review inputs. A merchandising specialist from BuyFast stated, "The livestream comments and post-purchase reviews became our real-time focus group. We weren't waiting for a quarterly report; we were adjusting product descriptions and even production plans within days based on what we saw." In Case B, the structured wear-test feedback from the consumer panel was indispensable for finalising the denim's technical specifications. This reviewing function, scaled and systematised by the platform, de-risks the innovation and bridges the gap between prototype and market success.

In summary, these three roles—Problem Setter, Problem Solver, and Reviewer—form a cooperative nexus in MU innovation. The empirical data demonstrates that their fluid adoption by different actors, facilitated by the e-commerce ecosystem, underpins the shared responsibility and continuous interaction that characterise effective value co-creation.

5.2. MU Collaborative Modes

Our empirical investigation into the two cases reveals that the engagement between manufacturers and users manifests through a spectrum of collaborative modes, each characterised by distinct levels of resource integration intensity and collaboration depth. These modes represent strategic choices for partners, contingent upon their objectives, capabilities, and the nature of the innovation challenge they face. The data from the fashion e-commerce ecosystems allow us to delineate and illustrate five primary modes: R&D Outsourcing, Technical Patent Cooperation, Resource Transfer (platform-based sharing), Strategic Alliance, and Integration (vertical M&A/holding).

The R&D Outsourcing Mode is characterised by relatively low resource integration and collaboration depth. In this mode, users contract specialised manufacturers to execute specific development tasks. This approach was observed in a supporting role within our cases, where brands leveraged external technical expertise to complement their own capabilities. As one product manager from an online-native brand noted, "For specific technical challenges, like perfecting a new fabric finish, it's more efficient to partner with a specialist mill that has the R&D staff and equipment. It allows us to stay agile and focus on our core design and marketing competencies." This mode enables users to tap into specialised knowledge and infrastructure without deep, ongoing coordination, thus optimising resource allocation for discrete tasks.

Conversely, the Technical Patent Cooperation Mode exhibits high collaboration depth with relatively lower resource integration, focusing on the joint creation and ownership of intellectual property. Case B serves as a prime exemplar, where BrandX and the fabric mill MillY engaged in deep R&D collaboration. This partnership resulted in joint patent filings for process modifications derived from their co-development efforts. A senior R&D lead from MillY explained, "This wasn't a simple buyer-supplier transaction. We were in the lab together with BrandX's team, iterating on the low-water indigo recipe. The joint patent was a natural outcome of this deeply integrated technical problem-solving." This mode underscores a commitment to shared technical advancement and the strategic management of co-created IP, without necessitating full resource merger.

The Resource Transfer Mode, frequently platform-mediated, involves high resource integration but often with less intensive, project-specific joint R&D. This mode leverages the ecosystem's ability to pool and channel distributed assets. In Case A, this was evident as Tmall's analytics and sales volume guarantees from BuyFast were transferred to underwrite Shandong Knit Co.'s initial production runs. At the same time, Xiaohongshu micro-influencers contributed user-generated content and styling knowledge. A platform manager from Tmall

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described this as "orchestrating idle resources across the network—be it data, capital, or creative input—and directing them towards a common innovation goal." This mode maximises collective intelligence by broadly integrating complementary resources from multiple entities within the platform ecosystem.

Moving towards greater integration and sustained cooperation, the Strategic Alliance Mode involves forming structured partnerships, such as joint innovation initiatives. While the cases demonstrated elements of this, interviews with platform managers highlighted its growing prevalence. For instance, an informant from the Tmall Innovation Centre detailed collaborations where "a brand and a manufacturer establish a dedicated 'co-creation lab' on our platform, with shared KPIs and roadmaps for seasonal collections." Such alliances are driven by shared long-term goals and complementary resources, aiming for mutual strategic benefits that are unattainable individually. They provide a formal framework for continuous learning and co-development beyond a single project.

The Integration Mode represents the highest level of integration and collaboration depth, typically achieved through vertical mergers or acquisitions. Although not fully observed in our two short-term cases, the interview data suggest it as a strategic direction for firms seeking to internalise innovation capabilities fully. A logistics provider working with major brands observed, "We see leading players considering acquisitions of key component suppliers or even tech startups to lock in core innovations and secure their supply chain." This mode, whether forward or backward integration, aims to bring critical stages of the value chain under unified control, thereby minimising coordination friction and accelerating innovation cycles. However, it requires significant capital and managerial commitment.

In practice, as evidenced by our cross-case analysis, collaborations are often hybridised, blending multiple modes. Case A combined Resource Transfer with a Strategic Alliance-like co-design program. Case B blended Technical Patent Cooperation with R&D Outsourcing elements. This strategic flexibility allows firms to tailor their collaborative approach to the specific risks, IP considerations, and opportunities at hand, a nuance that is central to understanding MU collaboration in dynamic e-commerce ecosystems.

5.3 MU Collaborative Process

The MU collaborative innovation process is not a linear sequence of steps but rather a dynamic and often iterative journey, with manufacturers and users engaging in distinct roles and adopting different modes at various stages. The framework identifies three primary process types, reflecting varying degrees of user and manufacturer leadership throughout the innovation lifecycle, illustrating the spectrum of collaborative engagement.

A clear sequence characterises the first process type: the user acts as the problem setter, the manufacturer as the problem solver, and the user again as the reviewer. This process effectively transfers the responsibilities of problem identification and solution validation to the user, allowing the manufacturer to concentrate its expertise on technical execution. A classic example of this is found in Case A. The problem was jointly identified by the fast-fashion retailer BuyFast, which highlighted the challenges of high return rates and trend churn, and the Xiaohongshu micro-influencer communities, which revealed the specific demand for modularity. As a product development manager from BuyFast stated, "Our role was to translate the operational pain points and the community's styling ideas into a clear technical brief for Shandong Knit Co. They were the experts in making it happen." Shandong Knit Co. then took on the role of problem solver, deploying its 3D knitting expertise to develop solutions. Finally, the users—both micro-influencers and the broader consumer base, as indicated by platform metrics—served as reviewers, validating the prototypes and the final product through livestream feedback and post-purchase data, leading to continuous refinement.

The second process type involves intensive joint problem-solving, where both manufacturer and user collaborate deeply throughout the R&D phase. This model features continuous, iterative interaction that goes far beyond initial briefings or final testing. Case B serves as a clear illustration. While BrandX and its consumer panel set the initial problem of creating commercially viable, sustainable denim, the subsequent development was a deeply collaborative effort. The fabric mill MillY was not a passive executor but an active co-creator. A

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technical lead from MillY described the process: "It wasn't a hand-off. We worked side by side with BrandX's team in joint lab sessions, adjusting the finishing recipe based on real-time feedback from their consumer wear tests. Our proposals were evaluated, and the design was adjusted in a loop." This process leveraged BrandX's market knowledge and MillY's technical prowess in a tightly integrated feedback loop, embodying a partnership where problems were actively solved together.

The third process type is defined by comprehensive leadership, where one entity—either the user or the manufacturer—takes charge of problem setting, problem solving, and reviewing across all stages. In user-led innovation, a powerful user drives the entire process to fulfil their strategic needs. While our cases demonstrated strong user leadership, interviews revealed even more pronounced examples. For instance, a merchandising specialist from a large retail group explained their approach: "For our private label, we don't just set the brief. We have an in-house tech team that works on material specifications and pattern engineering from day one. We set the problem based on our sales data, co-develop the solution with the factory's engineers, and conduct a final quality review against our own standards. The factory provides essential production capacity and technical support." This showcases how a dominant user can orchestrate the entire value chain. Conversely, in manufacturer-led innovation, the manufacturer assumes the primary visionary and driving role. This was observed in initiatives where manufacturers, armed with proprietary technology, proactively developed new product platforms and then engaged lead users for feedback and market integration, effectively leading the innovation trajectory while integrating user input for refinement.

In conclusion, the existence and application of these process types are not rigid but are strategically contingent. The choice depends on factors such as the specific capabilities of the firms involved, the nature of the innovation (incremental vs. radical), and the strategic intent of the collaboration, highlighting the inherently dynamic and adaptable nature of MU collaborative innovation within e-commerce ecosystems.

5.4 MU Collaborative Mechanisms

To ensure the effective functioning and sustainability of MU collaborative innovation, a set of underlying mechanisms facilitates interaction, manages knowledge, structures organisations, and leverages digital technologies. These mechanisms are crucial for maintaining systemic health and driving innovation forward by creating a supportive environment for co-creation.

The Strategic Collaboration Mechanism addresses the foundational alignment between manufacturers and users, focusing on the complementarity of their strategic identities and capabilities. Manufacturers typically aim to serve broad market needs with scalable products, whereas lead users often innovate to meet specific, advanced, or heterogeneous requirements that existing products cannot satisfy. Strategic collaboration helps bridge this gap, ensuring that innovation efforts address both general market demands and the specific needs of niche users. A user's foresight in identifying emerging technological trends or market opportunities can guide a manufacturer's R&D strategy, providing a strategic advantage by directing efforts toward high-potential areas. Conversely, a manufacturer's technical prowess and production capacity can enable users to achieve their advanced operational goals. The ability of users to initiate innovative procurement can create initial market scale, reduce market risk for manufacturers by demonstrating demand, and validate new products, offering powerful strategic incentives for collaboration. This mutual reinforcement, stemming from complementary identities and capabilities, is a primary driver for MU collaborative innovation. In Case B, BrandX's strategic need for verifiable sustainability aligned perfectly with MillY's goal of commercialising its proprietary low-water technology. A business development manager from MillY noted, "BrandX didn't just want to buy fabric; they wanted a technology partner to build a sustainable product line with. Their market pull gave our R&D a clear, commercially viable direction it previously lacked." Conversely, in Case A, Shandong Knit Co.'s strategic objective to move up the value chain was realised through BuyFast's commitment to a co-creation pilot, which de-risked the manufacturer's investment in flexible production. This strategic symbiosis ensures innovation efforts are simultaneously ambitious and grounded in market reality.

Central to any collaborative endeavour is the effective management of information and expertise, which the Knowledge Collaboration Mechanism encapsulates. This mechanism focuses on the mutual transformation and

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enhancement of both tacit and explicit knowledge between manufacturers and users. Users are invaluable sources of insight, particularly regarding unmet needs and practical application contexts. Their knowledge, often tacit and embedded in daily operations, is crucial for identifying genuine problems that may not be apparent to manufacturers. Manufacturers must develop strategies to capture this user knowledge, which can be challenging due to its implicit nature and the difficulty users may have in articulating abstract needs. Early engagement, continuous feedback loops, and co-design activities are crucial for capturing and converting insights into actionable information.

Furthermore, the mechanism addresses intellectual property (IP) disclosure and sharing. Users may choose to share IP—either for direct compensation or for indirect benefits, such as enhanced reputation, access to advanced solutions, or influence over industry standards. Manufacturers, in turn, leverage this shared knowledge to inform and refine their solutions. The use of a modular product architecture, for instance, can allow users to experiment and innovate with different configurations, with the manufacturer then capturing these innovations and integrating them into future product designs, creating a continuous knowledge feedback loop. Our findings underscore the crucial importance of early and ongoing engagement. In Case A, micro-influencers on Xiaohongshu provided "fit documentation" through videos, translating subjective comfort into actionable technical insights for Shandong Knit Co. A designer from a micro-brand emphasised the depth of this exchange: "The factory engineers initially didn't understand why a certain seam was uncomfortable until we showed them, in motion, how it restricted movement. That video was worth a thousand words in a spec sheet."

Regarding IP, Case B demonstrated a proactive approach. The joint patent filings and structured revenue-sharing agreements created a formal framework that incentivised open knowledge exchange. A technology provider observed, "Without clear IP rules upfront, that kind of deep laboratory collaboration between MillY and BrandX would never have happened. Trust is key, but a contract enables that trust."

Beyond individual interactions and knowledge flows, the Organisational Collaboration Mechanism structures the relationships between manufacturers and users. This involves designing new management approaches and organisational structures to manage what are often mixed inter-organisational relationships. One aspect is external collaboration, where manufacturers and users establish formal structures such as joint R&D teams, strategic alliances, or shared laboratories. These structures facilitate knowledge activation and continuous learning, offering a robust platform for sharing resources and technical complementarity. Joint laboratories between major industrial players and key clients for technology research, or open innovation centres where users and manufacturers co-develop solutions, exemplify how external organisational structures facilitate sustained co-development. Another aspect is internal collaboration, which involves integrating external entities into one's organisational structure through vertical integration or by adopting ambidextrous organisational designs. For instance, a manufacturer might acquire a key user (forward integration) or a critical component supplier (backward integration) to internalise the innovation process, gaining direct control over all stages. An entity acquiring a specialised component manufacturer enables seamless innovation in integrated systems. Similarly, some organisations create "maker spaces" or dual-structure units that can both leverage existing capabilities and explore new ones, effectively accommodating the diverse needs of collaborative innovation. A logistics provider working with major brands noted, "We're seeing leading apparel companies acquiring smaller, agile factories or tech startups. It's the ultimate way to internalise the innovation process and cut through coordination delays."

The Digital Collaboration Mechanism leverages advanced digital technologies to enhance and support MU collaborative innovation. This mechanism acknowledges the transformative power of tools like artificial intelligence (AI), big data analytics, digital platforms, and innovation toolkits. Digital technologies significantly enhance manufacturers' ability to identify and understand user needs, ideas, and lead users. AI algorithms can analyse vast datasets to pinpoint unmet demands or predict market trends, thereby streamlining the problem-setting phase and making it more data-driven. Digital toolkits and advanced software (e.g., computer-aided design, 3D printing, simulation platforms) empower users to participate more actively in the innovation process, allowing them to rapidly prototype ideas, test concepts, and provide precise feedback, effectively shifting towards more user-led innovation. These tools lower barriers to entry for user engagement and accelerate the iteration cycle.

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Furthermore, digital platforms facilitate seamless communication, collaboration, and knowledge exchange between manufacturers and users. An innovative product platform, for instance, can provide a digital ecosystem that enables users to interact with manufacturers, share feedback, and even co-create product features, thereby significantly enhancing responsiveness and continuous innovation by creating a virtual space for ongoing collaboration. By integrating these digital enablers, MU collaboration becomes more efficient, scalable, and responsive to evolving demands. A product manager from Tmall Innovation Centre highlighted the mechanism's efficiency: "Our analytics can identify a nascent trend from search and social data. We then use digital prototyping tools to quickly visualise concepts with brands and manufacturers, compressing months of market research into weeks."

Furthermore, livestreaming sessions served as a digital review platform, generating real-time, rich feedback that replaced slower, traditional focus groups. A livestreamer involved in a co-design session commented, "The comments fly in real-time—'I'd buy that if the collar were different' or 'That colour is perfect.' It's an immediate, massive focus group that directly influences the final product."

The theoretical framework for Manufacturer-User collaborative innovation offers a comprehensive lens through which to understand the intricate dynamics of modern innovation. By systematically analysing the roles, modes, processes, and mechanisms, it highlights how manufacturers and users can synergistically create value. This framework underscores the fundamental shift towards a more distributed and collaborative innovation paradigm, emphasising that successful technological advancement often stems from integrated efforts that leverage complementary strengths and foster continuous interaction. The insights derived from this framework provide valuable guidance for both academics and practitioners seeking to optimise collaborative innovation strategies in an increasingly interconnected and technologically driven world, moving beyond traditional, linear models to embrace a more dynamic and inclusive approach to creating new products, services, and solutions.

6. Cross-Case Insights and Mechanism Mapping

The comparative analysis of the two in-depth cases, complemented by interview data from diverse ecosystem stakeholders, reveals a coherent set of insights into how e-commerce ecosystems reconfigure manufacturer-user (MU) collaborative innovation networks. These insights are synthesised and mapped onto the integrated theoretical framework presented in Figure 1, which positions complementary collaboration as the core dynamic, supported by strategic guidance and three foundational mechanisms: knowledge, organisational, and digital collaboration.

6.1 Key Patterns from Cross-Cases Analysis

Lead User Heterogeneity and Role Fluidity. Our findings confirm that "lead users" in e-commerce ecosystems are not a monolithic group. In the fashion industry, they encompass distinct types—each contributing unique knowledge: 1) Large buyers and retailers (e.g., BuyFast), who bring operational scale, stringent quality standards, and volume-driven procurement power; 2) Micro-influencer communities (e.g., on Xiaohongshu), who provide tacit, trend-forward styling insights and real-world usage scenarios; and 3) Platform-recruited consumer panels, who offer structured feedback on specific attributes like sustainability or functionality. This heterogeneity necessitates that manufacturers and platforms tailor their engagement strategies. Moreover, the assignment of collaborative roles—Problem Setter, Problem Solver, Reviewer—is fluid rather than fixed. As evidenced in both cases, users frequently initiated the innovation (Problem Setter), co-designed solutions (co-Problem Solver), and validated outcomes through platform-mediated feedback (Reviewer). A Tmall product manager captured this fluidity: "The line between who defines the problem and who solves it is blurring. Users come with the insight, but they also stay in the digital room to tweak the 3D model with the factory."

Platform Orchestration as a Critical Enabler. E-commerce platforms do not merely connect parties; they actively architect collaboration. Their roles extend to: matchmaking (linking Shandong Knit Co. with BuyFast and micro-influencers), providing infrastructure (digital toolkits, analytics APIs, livestreaming studios), and setting governance (campaign rules, escrowed IP arrangements, reputation systems). This orchestration reduces transaction costs and enables collaboration at scale. In Case B, Tmall's co-creation campaign framework

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provided the necessary structure for BrandX, MillY, and consumer panels to interact iteratively, while its analytics converted user sentiment into actionable research and development (R&D) parameters.

Hybridisation of Collaborative Modes. Real-world MU collaborations rarely adhere to a single pure mode. Instead, firms strategically blend modes to balance risk, control, and resource commitments. Case A combined Resource Transfer (platform analytics and sales guarantees underpinning production) with elements of a Strategic Alliance (a structured co-design program). Case B blended Technical Patent Cooperation (joint IP development) with R&D Outsourcing (specific tasks contracted to the fabric mill). This hybridisation allows partners to maintain flexibility while deepening engagement where it matters most—be it IP creation, risk-sharing, or resource pooling.

Digital Mechanisms Reduce Information and Iteration Friction. The cases highlight how digital tools operationalise theoretical mechanisms. Datafication and AI analytics (e.g., Tmall's trend detection) transform latent user preferences into explicit, quantifiable inputs, directly informing the Problem Setting phase. Digital prototyping and 3D simulation tools (used by Shandong Knit Co.) enabled micro-influencers to co-solve design problems in near real-time, bridging tacit user knowledge with manufacturable specifications—a core function of the Knowledge Collaboration Mechanism. Livestreaming served as a powerful Digital Collaboration tool, creating an instantaneous, scalable review loop that replaced slower, traditional market testing. As one livestreamer noted, "The comments flow in real-time… It's like a massive, interactive focus group that directly shapes the product before it's even finalised."

Governance and Trust as Persistent Constraints. Despite digital efficiencies, collaboration remains underpinned by relational and contractual safeguards. Both cases underscored the necessity of preemptive IP agreements (e.g., joint patent filings and revenue-sharing in Case B) and risk-mitigating guarantees (e.g., BuyFast's volume commitment in Case A) to align incentives and encourage knowledge disclosure. The absence of such formal and informal governance structures was frequently cited in interviews as a barrier to deeper collaboration, highlighting that digital tools alone cannot fully substitute for trust and clear rules.

6.2 Mapping Insights onto the MU Collaborative Innovation Framework

The patterns above align with and empirically ground the components of the framework visualised in Figure 1:

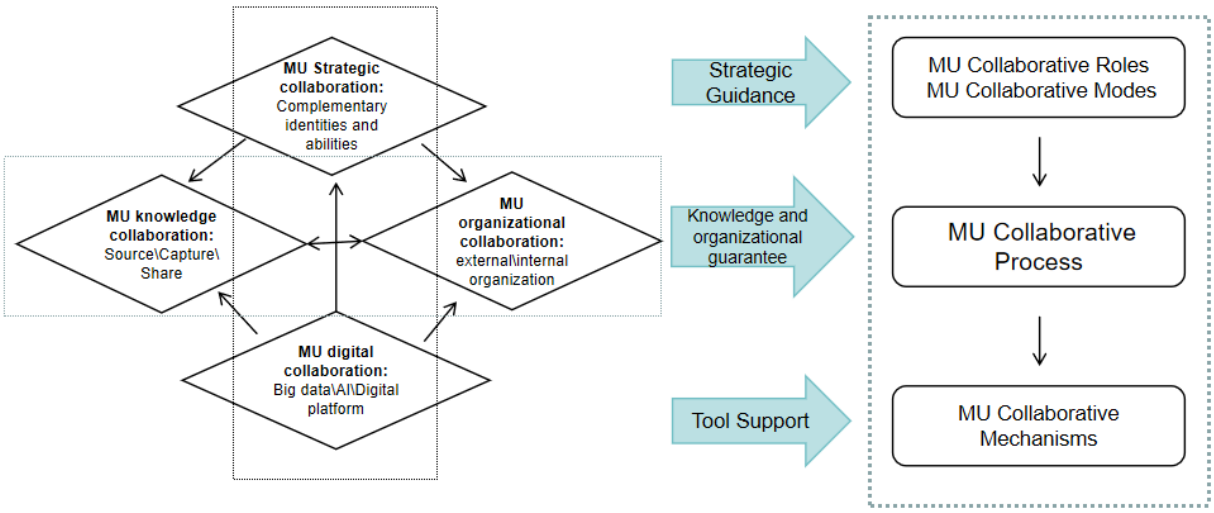


Figure 1. Core Components of Manufacturer-User (MU) Complementary Collaboration
Source: the authors

Strategic Guidance & Complementary Identities: The core driver of collaboration in both cases was the strategic complementarity between manufacturers' technical/production capabilities and users' market/contextual knowledge. For example, Shandong Knit Co.'s ambition to move up the value chain complemented BuyFast's need for agile, personalised supply—forming the strategic rationale for their alliance.

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MU Collaborative Roles and Modes: The observed role fluidity and mode hybridisation are operational manifestations of this strategic complementarity. The framework's separation of Roles, Modes, and Processes helps dissect how a single collaboration (e.g., Case A) can involve users shifting between being setters, solvers, and reviewers. At the same time, the partnership itself blends multiple formal modes.

Knowledge, Organisational, and Digital Collaboration Mechanisms: The three support pillars of the framework were actively at work: Knowledge Collaboration was evident in the translation of micro-influencers' "fit documentation" into technical parameters (Case A) and the joint laboratory sessions between BrandX and MillY (Case B). Organisational Collaboration manifested in the creation of temporary but structured co-creation units (e.g., the joint "lab" sessions in Case B, the platform-facilitated project team in Case A). It was discussed as a strategic goal in interviews, indicating a potential for vertical integration. Digital Collaboration was the pervasive enabler, with platform analytics, digital toolkits, and livestreaming serving as the technical infrastructure that made the other two mechanisms scalable and efficient.

6.3 Synthesis: The Platform-Mediated Reconfiguration

Collectively, these insights demonstrate that e-commerce ecosystems reconfigure MU innovation networks by institutionalising the mechanisms that enable complementary collaboration. Platforms compress the innovation cycle not just by speeding up information flows, but by providing an integrated architecture where strategic alignment is facilitated, knowledge exchange is structured, organisational boundaries are softened, and digital tools are embedded. This reconfiguration shifts innovation from a linear, manufacturer-centric process to a dynamic, multi-actor network where users are empowered participants and value is co-created iteratively. However, this study also confirms that this new architecture introduces its own governance complexities, particularly around IP and trust, which require deliberate managerial and platform-level design to ensure sustainable collaboration.

7. Findings

The findings of this study illuminate the nuanced dynamics of manufacturer-user (MU) collaborative innovation within a digitally-mediated context. By grounding the investigation in China's fashion and apparel e-commerce ecosystems, this research makes distinct contributions to both the evolving literature on platform-driven innovation ecosystems and the empirical understanding of innovation processes in a fast-cycle, consumer-facing industry. Beyond these contextual contributions, the study advances theoretical integration by bridging previously siloed perspectives.

Contributions to the Understanding of E-commerce Ecosystems

This research refines the conceptualisation of e-commerce ecosystems from mere transactional or social platforms to active architects of innovation networks. Prior platform literature has emphasised matchmaking and transaction efficiency. Our findings extend this view by empirically demonstrating how platforms perform critical orchestration functions that structurally reconfigure MU collaboration: they codify tacit user knowledge into actionable data, formalise hybrid collaboration modes (e.g., blending resource transfer with strategic alliances), and institutionalise governance mechanisms (e.g., escrowed IP, staged disclosure) that mitigate the inherent risks of co-creation. The study thus positions platforms not as passive infrastructure but as proactive agents that set the rules, provide the tools, and curate the participants for innovation, thereby directly shaping the "how" of MU collaboration in the digital age.

Insights for the Fashion and Apparel Industry

The fashion industry, characterised by short product lifecycles, volatile trends, and rising demand for personalisation and sustainability, serves as an ideal crucible for observing MU collaboration. This study offers a granular, process-oriented perspective on how digital ecosystems enable the industry to address its core challenges. First, it documents the operationalisation of agility: platforms compress design-to-market cycles by integrating real-time user feedback (via livestreaming, UGC analytics) directly into flexible, on-demand production systems (e.g., 3D knitting). Second, it reveals how sustainability transitions can be accelerated through platform-mediated collaborations, as seen in Case B, where consumer panel data and co-development

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with a fabric mill de-risked the commercialisation of a novel eco-technology. These insights move beyond general statements about "digital transformation" to show the specific, replicable mechanisms—such as modular co-design and data-driven validation loops—that allow fashion firms to achieve both commercial responsiveness and strategic innovation.

Theoretical Integration and Advancement

At the theoretical level, this study's primary contribution lies in developing and empirically validating an integrated framework that connects macro-level ecosystem structures with micro-level collaborative practices. We achieve this by synthesising three theoretical streams: service-dominant logic (resource integration and value co-creation), post-Schumpeterian/user innovation theory (the agency of lead users), and platform ecosystem theory (the governance and architectural roles of intermediaries).

Specifically, the study advances theory in four ways:

Role Fluidity and Platform-Induced Blurring: It empirically challenges static role typologies by demonstrating that in platform ecosystems, the functions of Problem Setter, Solver, and Reviewer are fluid and often shared. Users are not just sources of requirement but active co-solvers via digital toolkits.

Mode Hybridisation as a Strategic Response: It shows that classical, discrete collaboration modes (e.g., R&D outsourcing, alliances) are strategically blended in practice. This hybridisation is a direct response to the high uncertainty, IP sensitivity, and resource-distributed nature of platform-mediated innovation.

Mechanistic Bridging of Knowledge Asymmetry: It delineates the specific knowledge, organisational, and digital mechanisms that work in concert to bridge the classic manufacturer-user knowledge gap. The Digital Collaboration Mechanism, in particular, is shown not as a standalone force but as the enabler that scales and accelerates the other two.

Introducing Platform Governance as a Core Mediating Layer: The study highlights that the success of MU collaboration is contingent not only on bilateral firm strategies but also on the platform's governance layer—its rules, incentive designs, and trust-building tools. This positions platform governance as a critical new variable in models of inter-firm innovation.

In conclusion, this discussion underscores that the reconfiguration of MU innovation networks within e-commerce ecosystems is a multifaceted phenomenon. It is driven by the strategic complementarity of actors, enabled and shaped by the architectural and governance power of platforms, and operationalised through a set of intertwined mechanisms that are vividly exemplified in the dynamic context of the fashion industry. This integrated perspective offers a more complete toolkit for both researchers studying digital innovation and practitioners navigating collaborative strategies in platform-dominated markets.

8. Implications

The insights derived from this study extend beyond theoretical enrichment, offering actionable guidance for key stakeholders navigating the platform-mediated landscape of collaborative innovation. The implications are delineated for manufacturers, lead users (including retailers and brands), platform orchestrators, and policymakers.

Implications for Manufacturers

For manufacturers, particularly OEMs and component suppliers seeking to move beyond commoditised production, this study underscores the imperative to evolve from passive executors to active co-innovation partners. First, strategic prioritisation of digital absorptive capacity is crucial. Investing in and mastering digital toolkits—such as 3D simulation, virtual prototyping, and data analytics interfaces—is no longer optional. These tools serve as essential translators, converting tacit user feedback (e.g., influencer fit videos) into precise, manufacturable specifications, as demonstrated by Shandong Knit Co.'s use of virtual fit simulation. Second, operational flexibility must be engineered into production systems. Adopting small-batch, on-demand

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capabilities (such as 3D knitting or modular assembly) enables manufacturers to participate in platform-led co-creation pilots without incurring prohibitive inventory risks. This flexibility was key to de-risking the collaboration in Case A. Third, a proactive approach to partnership governance is necessary. Manufacturers should initiate clear agreements on intellectual property (IP) ownership, revenue sharing, and data usage at the outset of collaboration. The joint patent and revenue-sharing model in Case B demonstrates how such formal frameworks can protect interests while fostering deep knowledge exchange, turning collaborative projects into sustained strategic advantages rather than one-off transactions.

Implications for Lead Users (Retailers, Brands, and Influential Communities)

Lead users, who possess market influence and contextual knowledge, can leverage platform ecosystems to drive innovation that directly addresses their strategic challenges. They should act as orchestrators of demand articulation and risk mitigation. This involves using platform analytics not just for trend spotting but to construct data-rich problem statements that clearly define innovation parameters for manufacturers, as BuyFast did by linking return-rate issues to modularity trends. Furthermore, lead users can de-risk manufacturer participation by offering tangible commitments, such as pre-sales volume guarantees or access to exclusive consumer panels. These signals of market intent lower the barrier for manufacturers to invest in flexible, collaborative production. Finally, engaging in iterative, micro-scale validation through platform features such as livestreamed co-design sessions or limited pilot releases allows lead users to test and refine concepts with real consumers before a full-scale launch, transforming market validation from a post-hoc checkpoint into an integrated part of the development process.

Implications for Platform Designers and Orchestrators

For e-commerce platforms aiming to transcend their transactional role and become innovation ecosystems, this research highlights critical design imperatives. Platforms must consciously design governance to foster trust. This involves developing and implementing robust mechanisms such as escrowed IP agreements, staged disclosure protocols, and transparent reputation systems. These tools mitigate the collaboration-inhibiting fears of appropriation and misappropriation identified in the cases. Secondly, platforms should curate and empower boundary-spanning intermediaries. The study highlights the emerging role of agencies and studios in translating user needs into technical briefs. Platforms can facilitate this by certifying service providers, creating standardised co-creation protocols, and offering matchmaking services that connect manufacturers with the correct type of lead user (e.g., micro-influencer vs. large retailer). Lastly, democratising access to innovation tools is key. Providing user-friendly digital toolkits, analytics dashboards, and collaboration features lowers the entry barrier for SMEs and diverse user groups, enabling a broader and more vibrant ecosystem of co-creation, which in turn enhances the platform's value and stickiness.

Implications for Policymakers

Policymakers interested in fostering innovation-led growth and digital economy competitiveness can derive several insights. There is a pressing need to modernise regulatory frameworks for the data-driven, collaborative economy. This includes clarifying IP rights over co-created innovations and user-generated data, establishing guidelines for fair data sharing between platforms and business users, and ensuring competition policies account for the gatekeeping power of platform orchestrators in innovation networks. Additionally, policymakers can promote the diffusion of collaborative innovation models by supporting the development of industry-wide standards and certification schemes, particularly in areas such as sustainability metrics. Verified standards reduce transaction costs and build trust, as seen in the market premium for the certified sustainable denim in Case B. Finally, public investment in workforce upskilling for digital manufacturing and co-design competencies can ensure that smaller manufacturers and designers have the necessary skills to participate effectively in platform-mediated innovation, preventing a digital divide within industrial ecosystems.

9. Limitations and Future Research Directions

While this study offers valuable insights, it is bounded by several limitations that pave the way for future inquiry. First, the findings are contextualised within China's fashion and apparel e-commerce ecosystem. The unique dynamism of this market and the specific structure of its platforms may limit direct generalizability to other

industries (e.g., durable goods) or institutional contexts (e.g., markets with different data governance regimes). Second, the research design prioritised mechanistic depth through qualitative case studies, which, while rich in detail, do not provide statistical representativeness or allow for broad causal claims. Third, access to proprietary platform algorithms and complete transactional datasets was constrained, meaning some underlying drivers of matchmaking and trend prediction could only be inferred from interviews and outcomes.

These limitations suggest several promising avenues for future research. Comparative studies across different national markets (e.g., comparing China with the EU or the US) or industrial sectors could elucidate how regulatory environments and industry structures shape MU collaboration models. Longitudinal research tracking firms that institutionalise platform-based co-innovation would be valuable to examine long-term capability development and competitive outcomes. To complement our qualitative findings, large-scale quantitative studies leveraging platform partner data could rigorously test the performance implications of different collaborative roles, modes, and governance mechanisms. Finally, research could delve deeper into specific thematic areas highlighted here, such as the optimal design of platform governance for IP sharing in open innovation, or the role of AI agents in further automating and personalising the co-creation process.

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NAVIGATING TECHNOLOGY ADOPTION IN SMALL BUSINESSES OPERATING IN A SOUTH AFRICAN TOWNSHIP

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Abstract. The integration of Information and Communications Technology has become essential for business operations globally, including small businesses in South African townships. The rapid technological advancements and the impact of the COVID-19 pandemic have accelerated the need for digital integration. This study employs a qualitative methodology, analysing thirty academic publications post-COVID-19, to explore the use of technology in township small businesses. While technology adoption has been linked to business success, its utilisation in township businesses remains partial due to various challenges such as digital illiteracy, infrastructural constraints, and a lack of clear policies. The study highlights the benefits of technology integration and calls for future research to identify optimal technological solutions for small businesses in townships. It also emphasises the need for targeted support, including policy frameworks, training programmes, and infrastructural improvements, to enhance digital adoption in these environments.

Keywords: small businesses, technology adoption, township economy

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JEL Classifications: O31, O33

1. Introduction

The emergence of Information and Communications Technology (ICT) is now becoming a core operation in businesses in South Africa and worldwide. From micro-enterprises to multinational corporations, the integration of ICT has transformed business processes, reshaped customer engagement, and enabled access to new markets (Slinger et al., 2024; Gavaza et al., 2025b). This digital transformation has reached even the most underserved areas and localities in South Africa, including townships, where the establishment of small businesses is a significant segment of the informal economy (Marolt et al., 2025). The COVID-19 pandemic accelerated this trend by forcing many businesses, regardless of size, to enter the digital space to remain operational (Cromhout & Duffett, 2022). Small businesses situated in a township, even those that were not so inclined to use digital tools before, were forced to be involved in technology, but at different levels and with varying degrees of sophistication.

The business domain is now more complex regarding innovation, creativity, production, transactions, and communication channels between the business and its surroundings (Tshabalala & Beharry-Ramraj, 2021). The COVID-19 pandemic era almost compelled every business to adopt technology, including small businesses in

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townships (Dos Santos & Duffett, 2021). Due to the introduction of WhatsApp, Facebook Marketplace, and mobile point-of-sale systems, traditional methods can no longer effectively help small businesses in townships to market their items, conduct transactions, and foster customer loyalty. The use of technology, particularly the Internet, has eliminated geographical boundaries and historical barriers between township entrepreneurial businesses and the customer community. Engaging the customer community is essential, as customer feedback presents an opportunity to address any negative instances (Amankwah-amoah et al., 2021). This helps establish customer relationships that lead to customer retention, especially when customers perceive they are part of the business (Cromhout & Duffett, 2022). Thus, appropriate technologies are essential to meeting customers' needs (Bomani et al., 2024).

Despite these advances, the township sector remains a difficult terrain to map (Township Tech Sector Intelligence Report, 2021). This is especially true because townships have a wide variety of business types, operations are usually unstructured, and the infrastructure is not evenly distributed, making empirical research in these environments quite challenging (Kayser et al., 2023). Thus, entrepreneurs operating within township setups do not always work within more established regulatory and financial frameworks, limiting their exposure and the ability to receive more formalised forms of assistance (Bingwa, 2024). Furthermore, there is no consistency in the adoption rate of technology by the township businesses, and it is therefore less likely to form general trends and best practices (Shibiti et al., 2023). The adoption of digital tools is complete in some businesses and negligible to nil in others due to cost, digital illiteracy, and infrastructural constraints (Dos Santos & Duffett, 2021; Muchineripi, 2025). As such, researchers face significant challenges when gathering information and arriving at uniform findings regarding digital uptake in townships.

However, following the COVID-19 pandemic, a trend has emerged in township entrepreneurship. The contribution of these small businesses to the township's economy is becoming increasingly visible (Gavaza, 2025; Shibiti et al., 2023). There is an increase in literature on township economies, and the trend of digital entrepreneurship and adoption of technology is getting considerable attention (Tau et al., 2024). Nevertheless, most of the published literature focuses on either general entrepreneurship or urban small businesses, whereas little is known about the peculiarities of technological utilisation in township environments (Akinsola & Munepapa, 2021). Systematic knowledge regarding the level to which township businesses adopted technology, the problems they encounter, and which strategies would contribute to deeper digitalisation remains limited.

The latest surveys indicate that, on the one hand, 72 per cent of South African urban SMEs have implemented at least one digital tool. At the same time, adoption rates among township small businesses are estimated to be less than 40%, revealing a stark contrast (Small Enterprise Development Agency, 2023). Similar results have been observed in other African countries, with Kenya having 32 per cent of small businesses still failing to fully utilise digital technology, despite the high penetration of technology in Africa (Muli & Eising, 2020). This paper aims to fill that gap by implementing a cumulative literature review study on the topic of technology in township small businesses in South Africa, particularly in the context of the COVID-19 pandemic. It examines in particular the technology adopted, perceived usefulness, ease of use, and structural and behavioural barriers to adoption. The Technology Acceptance Model forms the basis of the study, offering a theoretical perspective through which the results can be interpreted, explaining how entrepreneurs perceive and approach the use of technology. Therefore, this study aims to investigate the use and acceptance of technology in township small businesses in South Africa. Furthermore, to provide strategies to assist technology adoption in township small businesses.

2. Literature Review

Technology Acceptance and Adoption in Township Economies

The concept of technology adoption is extensively discussed in business and information systems-oriented literature, and several models have been developed to substantiate the behavioural and contextual factors that influence adoption (Madzvamuse et al., 2024). The Technology Acceptance Model (TAM) by Davis (1993) is one of the most established frameworks and remains a key instrument in understanding the motivation to accept or reject digital innovations among users. TAM posits that two key perceptions, perceived usefulness and perceived ease of use, shape an individual's behavioural intention to use a technology (Davis, 1993). These

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constructs are especially applicable in the township's small businesses. To that end, entrepreneurs frequently evaluate the potential of the technology to enhance customer engagement, boost sales, or facilitate business processes (Slinger et al., 2024). Accordingly, mobile point-of-sale (POS) devices, e-wallets, and social media platforms would be increasingly adopted if they are perceived as offering immediate value to companies.

Equally important is the ease of use, especially given that many township entrepreneurs operate without formal ICT training or access to digital literacy resources (Almawash & Saleh, 2024). Small owners may be deterred by the presence of complex interfaces or multi-layered systems, lacking the necessary technical knowledge or confidence to utilise them (Mukuni, 2023). This is why platforms with even an easier user experience, such as WhatsApp Business and Facebook Marketplace, are widely used in townships, which require minimal onboarding (Donga & Chimucheka, 2025). They have become popular not just because they are simple, but also because they align with current customer behaviour, such as mobile messaging and social media browsing, among others.

However, the literature also identifies perceived risk and trust as additional factors influencing adoption (Cromhout & Duffett, 2022; Dos Santos & Duffett, 2021). The most frequent reason given by township entrepreneurs for their choices to opt in or opt out of mobile banking or electronic payment platforms is the concern of fraud, identity theft, or technical difficulties (Bhatt, 2016). Consumer confidence in service providers, especially in geographical locations where financial fraudsters and unsupportive after-sales services are prevalent, significantly influences adoption choices (Tshabalala & Beharry-Ramraj, 2021). Without ensuring that their data is safe and support can be offered in case of failure, entrepreneurs will not adopt new technology, despite the perceived high benefits of using it.

Technology penetration in the township environment is, in practice, neither linear nor comprehensive (Asongu, 2021). Instead, it is more likely to be in the form of a hybrid, where the digital toolbox objects are deployed alongside established practices. For example, a business owner can sell products through Facebook or WhatsApp; however, they can still manage inventory and customer profiles manually (Nhuvira & Dorasamy, 2021). This is a partial embrace of creativity and constraints; businesses would do what they can with the provided infrastructural constraints, cost constraints, and support gaps. Despite the level of interest in technology, structural issues often hinder the full integration process, as they are beyond the control of individual entrepreneurs (Ligthelm, 2016).

Furthermore, the broader policy environment has fallen short of adequately meeting the demands for digital inclusion in township economies (Marolt et al., 2025). Nationally designed initiatives to increase connectivity, such as SA Connect and the Digital Migration Strategy, are often misplaced because they frequently fail to incorporate implementation processes directly applicable to informal micro-enterprises (Nhuvira & Dorasamy, 2021). Therefore, there is a fragmentation of technology adoption that is unbalanced and prone to failure under the same circumstances unless such initiatives are facilitated by coordinated infrastructure, capacity building, and institutional support (dos Santos & Duffett, 2021).

Overview of Township Small Businesses in South Africa

Small businesses in the townships are a pillar of the informal and formal economy of South Africa. The variety of these businesses includes spaza shops, hairdressing salons, car washes, food sellers, informal manufacturers, and repair services (Ligthelm, 2008). Although they are not homogeneous, they face similar challenges, such as limited access to formal financial systems, inadequate security in business premises, and low customer demand (Otieno & Wawire, 2023). Most of them are not registered and cannot access the government support, credit, and training programmes. However, they remain a source of income for millions of people, especially in societies where unemployment is rampant. The legacy of apartheid forced most townships outside the economic centres, causing logistical issues with transporting goods, reaching customers, or involving them in wider supply chains (Bingwa, 2024). The infrastructure of townships, including roads, electricity, broadband, and even public safety, can be underdeveloped or poorly maintained (Kayser et al., 2023). This leaves entrepreneurs with no option but to rely solely on local networks to source and sell, and create informal support networks, which act as an alternative to formal market access.

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Regardless of the structural obstacles to growth, township economies are gradually gaining recognition for their resilience and innovation. A flexible pricing structure, word-of-mouth marketing, and effective community relations enable small businesses to respond promptly to changing events (Chingapi & Steyn, 2022). The Township and Rural Economy Revitalisation Strategy recognises the crucial role of township businesses in fostering inclusive economic growth (Department of Small Business Development, 2023). Nonetheless, in practice, it is implemented slowly and lacks sufficient resources (Muchineripi et al., 2025). Most programs do not consider the lived realities of informal entrepreneurs, particularly in terms of digital inclusion and access to modern technology (Small Town Regeneration Strategy and Implementation Plan, 2021). Small businesses in townships play a crucial role due to their social value, particularly to economically and socially disadvantaged groups. Therefore, township small businesses are not only a source of income but also a means of skill fine-tuning, social capital building, and contributing to the economy (Kayser et al., 2023). Although some township businesses have taken steps to formalise their activities, most, if not all, have not registered their businesses, and they operate on the fringes of the formal economy (Slinger et al., 2024). As a result, most township small businesses are exposed to economic shocks, regulatory tightening, crime, and natural disasters, which negatively impact the informal sector (Mbatha et al., 2024). Given the complexities of the township environment, academic researchers increasingly agree that township small businesses require targeted support that reflects their unique operating conditions (Dos Santos & Duffett, 2021; Mbatha et al., 2024).

Technology Use in Township Small Businesses

Digital technology has created new opportunities for township entrepreneurs, especially in areas such as marketing, transactions, and customer services (Ojong et al., 2021). Social networks, such as WhatsApp, Facebook, and Instagram, are widely used to market goods and services, interact with customers, and take informal orders (Dos Santos & Duffett, 2021). These platforms are attractive because they are simple to operate and relatively inexpensive to use, as small business owners and customers are familiar with them, making them particularly appealing in low-income township settings (Tau et al., 2024). Furthermore, social networks are also utilised to maintain relationships with customers, provide information about products, and facilitate delivery requests, thereby increasing customer loyalty and convenience (Abdul-Halim et al., 2022).

It is worth noting that certain township businesses have implemented mobile point-of-sale (POS) systems, such as Yoco and SnapScan, which enable them to accept card payments and reduce their reliance on cash (Tshabalala & Beharry-Ramraj, 2021). These solutions are particularly useful in addressing customer preference changes in a post-COVID-19 pandemic economy, where contactless payments are becoming increasingly accepted. However, they are only restricted to small businesses in particular townships, such as retail and food services, and do not often include businesses in construction-related jobs, repair, or casual manufacturing (Chingapi & Steyn, 2022).

The adoption of digital technology in township small businesses is essential (Madzvamuse et al., 2024). Many small business owners adopt the use of digital tools as a stopgap measure, primarily as an instrument of advertisement or communication (Slinger et al., 2024). Paul et al. (2024) argue that few township small business entrepreneurs utilise digital technology for bookkeeping and inventory management, or reach out to suppliers, thereby missing a significant opportunity to become more efficient and scalable. This stems from multiple interlinked barriers, including limited access to reliable internet, frequent power outages, unaffordable data, and the high cost of smart devices (Dos Santos & Duffett, 2021). In addition, Muchineripi et al. (2025) suggest that the issues of language, the lack of customer services, and the fear of being a victim of online fraud exacerbate the problem.

The Small Town Regeneration Strategy and Implementation Plan (2021) highlighted the need to train and support township small business owners in utilising digital technology. The majority of township entrepreneurs end up learning how to use digital tools informally, either through trial and error, word of mouth, or community-based sharing (Maichum et al., 2016). This indicates flexibility, which also makes the knowledge inconsistent and less confident in handling higher-scaled digital tools (Bhoola & Chetty, 2022). Additionally, people have a limited understanding of government and NGO activities related to digital empowerment (Almawash & Saleh, 2024). In cases where such programs do exist, they tend to focus on formal small businesses, or the program becomes invisible in township environments (Hongoro et al., 2022). Thus, one can conclude that the digital

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revolution has established itself in the formal sectors but remains to be systematically and large-scale in the township context (Gavaza et al., 2025a; Tau et al., 2024). Digital tools are, therefore, regarded as peripheral assets rather than core business assets (Joseph & Sengul, 2024). This highlights the need for integrated efforts to pursue a combination of infrastructure, affordability, skills, and ongoing support in township settings.

Identified Gaps and Study Rationale

Although the literature indicates a common consensus on the benefits of adopting digital technology amongst township small businesses, several key gaps exist therein. The empirical research on township informal businesses is limited compared to formal and urban small businesses. This urban-centred emphasis does not accurately reflect the realities of township economies, particularly in terms of their structural and socio-economic aspects. Furthermore, critical case studies documenting both successes and failures, as well as partial successes, of digital tools are under-reported, which is essential for understanding the entire range of dynamics of adoption (Cromhout & Duffett, 2022). Additionally, the lack of proper analysis of the interactions between policy frameworks, socio-cultural influences, and constraints under which township entrepreneurs are forced to operate is a common issue in the existing literature (Dos Santos & Duffett, 2021). This absence of a subtle, multi-layered analysis undermines the possibility of developing effective intervention programs specifically for the township environment settings.

In addition, integrated models between the micro-level perceptions of entrepreneurship, such as motivations, attitudes, and informal learning, and the macro-level of policy and institutional frameworks that enable the environment are significantly absent (Muchineripi et al., 2025). This research study bridges these gaps by developing a context-sensitive systematic analysis of digital technology adoption in township small businesses within the South African context. It directly implicates entrepreneurs, their views, the infrastructural and socio-economic hurdles they face, and even their policy landscape. Additionally, this research achieves a systematic review of the interaction of perceived usefulness, perceived ease of use, and facilitating conditions to impact digital usage in a township environment by using the TAM as a controlling theoretical perspective.

3. Methodology

Research Design

The study employed a qualitative systematic literature review design (SLR) approach to examine the digital technology adoption within township small businesses in South Africa. The SLR methodology was chosen based on its ability to be methodological and transparent, enabling the extensive identification, selection and synthesis of academically and policy-related literature (Bai et al., 2019). In comparison to the narrative reviews, systematic reviews have a predetermined protocol, which enhances the reliability, lineage, and quality of the research process (Boell & Cecez-Kecmanovic, 2014). The qualitative orientation was suitable for the exploratory nature of the study, as it was capable of indicating the subtle societal, infrastructural, and behavioural confines that inform technology uptake in informal sectors of the economy.

Methodological Framework

A hermeneutic approach proposed by Boell and Cecez-Kecmanovic (2014), which perceives the literature review process as itinerant and reflexive in nature, was used in this study. Thus, it allowed for continuous adjustment of the research scope in light of new findings and provided both methodological rigour and flexibility in analysis. Seven interconnected steps were used to review the process. First, an organised search was performed across several scholarly databases, including Google Scholar, Scopus, JSTOR, and ScienceDirect, to retrieve peer-reviewed articles, policy papers, and grey literature pertinent to digital technology adoption in township small businesses. At the second step, sorting, only the duplicates, outdated and irrelevant articles are filtered out. Sources before 2020 were excluded to maintain relevance, considering the rise of technological digitisation in township small businesses following the COVID-19 pandemic.

The third one, selection, involved the application of predetermined inclusion and exclusion criteria. The documents to be included satisfied the following criteria: they dealt with small businesses, were set in South Africa or other comparable developing township environments, discussed technology adoption and its use, and were in full text in English. Research that focused on localised attention of urban businesses or irrelevant ICT

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was not considered. The fourth step, that is, acquiring, involved downloading and organising the obtained literature into a referencing management system to enable the annotation, retrieval, and review of the literature.

Fifth, each document was read thoroughly. The important ideas, observations, and theoretical knowledge were mentioned and contrasted in the works—the sixth step involved identifying, which entailed inductive coding of the literature to identify emerging themes. Lastly, recursive interaction with literature was possible during the refining phase. Since new themes and patterns emerged during the reading and interpretation process, the preceding steps, such as searching or selecting, were revisited to fill gaps in concepts or expand the thematic coverage. This back-and-forth looping also promoted the strength and credibility of the thematic synthesis. The hermeneutic practice thereby made for a pliable but stringent treatment of the construction of literature, perfect in the discovery of subtle concerns within a multidimensional and changing discipline of research (Boell & Cecez-Kecmanovic, 2014).

Data Sources

Secondary data was collected for this study. A total of thirty academic sources were collected. The sources included peer-reviewed journal articles, government policy reports and practitioner publications. The focus was given to the literature published after 2020, as it reflects the timeframe within which the concept of digital transformation became more intensive in South African townships. The period of the COVID-19 pandemic (2020) was considered a critical period when the trends of digital adoption intensified.

Data Analysis and Synthesis

Thematic analyses were employed for this study. Inductive coding enables the emergence of themes within the literature; instead of being pre-imposed, themes emerge naturally (Bihu, 2024). Higher-order themes, in which codes were categorised, included partial technology adoption, trust and perceived risk, infrastructure and cost barriers, and policy absence. The qualitative approach helped the researcher to preserve the richness and depth of original studies in engaging a new integrative view on a given matter.

Data Trustworthiness

The study ensured transparency by documenting search terms, inclusion and exclusion criteria, and decision-making choices. Credibility was maintained through iterative analysis and checks with academic scholars, as well as triangulation using literature styles and fields (Hamilton & Finley, 2020). The dependability of the coding process was achieved by providing an audit trail of the coding procedure, while confirmability was established through the use of writing memos and analytic reflexivity. The researcher repeatedly revisited previous interpretations to identify and address any possible bias or omission.

Ethical Considerations

This systematic literature review was a desk-based type of research, and as such, it involved no human participants and no collection of primary data. However, the work met the academic requirements regarding ethical codes, including the formulation of correct references, the elimination of plagiarism, and sensitivity in interpreting the materials used (Badu et al., 2019). All literature utilised in the review was open to the public, and due credit was accorded to them in the review.

Limitations and Mitigation Strategies

The features of the hermeneutic approach have their limitations, nevertheless. The significant shortcoming is that subjective thematic identification and interpretation are possible. To address this concern, the researcher maintained a clear audit trail, recording the decision-making processes, and employed iterative memo writing to capture reflective ideas. Additionally, the researcher practised peer debriefing sessions with colleagues familiar with the areas of digital adoption research and the study of the township's small businesses. Furthermore, although the hermeneutic approach is rich in profound results, it is not favourable to quantitative generalisation and statistical representativeness. Nevertheless, this weakness is reasonable because exploratory research questions focus on contextual rather than generalisable knowledge. It was not an exercise to deliver generalisable numerical findings, but rather an attempt to acquire sophisticated, contextually developed theoretical knowledge regarding the use of digital technology by township small businesses.

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4. Results

Technology Enhances Business Performance

The evidence in the literature supports the idea that digital technology significantly contributes to the improvement of operational and financial performance in small businesses within township environments. Research indicates that the implementation of facilities such as mobile point-of-sale (POS) systems, e-wallets, and social media platforms helps small businesses grow their customer base, increase revenue, and make their operations more efficient (Tshabalala & Beharry-Ramraj, 2021). Small companies that implemented digital technologies in their operations, such as WhatsApp for Business or Facebook Marketplace, had better customer contact, increased awareness, and faster availability (Dos Santos & Duffett, 2021). Moreover, mobile payment systems like Yoco and SnapScan have enabled an increase in financial inclusion by reducing the reliance on cash and facilitating card payments in regions that previously lacked these options. On balance, the reference literature emphasises that the implementation of digital technology, even in a limited capacity, has a positive influence on the productivity of small businesses, customer engagement, and transaction efficiency.

Partial and Uneven Technology Adoption

Despite the numerous benefits of digital technology, its use in township small businesses is intermittent and limited to the most basic applications. The review demonstrates that the majority of township small businesses focus on marketing and communication as the primary areas of utilising digital tools, whereas the rest of their operations, including inventory management, accounting, and supplier arrangement, are manual (Bhoola & Chetty, 2022; Shibiti et al., 2023). This selective use is explained by overlapping obstacles, including low digital literacy skills, inaccessible data charges, poor internet connectivity, and training deficits (Mapanga & Gavaza, 2025; Mbatha et al., 2024). The implementation of digital technology by many townships' small businesses is highly fragmented and improvised, introducing digital tools into some parts of the work process, while leaving others still to use an analogue system as the basic framework of business processes. This produces a mixed operating environment that is informed by the interest in innovation and the same enduring structural limitations.

Lack of Policy and Institutional Support

The study's findings showed a lack of proper policy frameworks to guide and support the adoption of digital technology in the township environment. National plans, such as SA Connect and the National Development Plan, recognise digital technology inclusion as a requirement; however, these plans often undermine the requirements of small businesses operating in townships (Department of Small Business Development, 2023). Some studies indicate that township small businesses lack adequate support and training, as evident in policy gaps, incoherent institutional efforts, and poor outreach have failed to provide sufficient support to these businesses (Bvuma & Marnewick, 2020; Gaglio et al., 2022). Moreover, the programs of digital technology development tend to focus on the urban formal economy, neglecting the peculiarities of the setting and demands of the township environment in which small businesses operate, which often exist outside the framework of formal regulation and funding channels. These informalities of direction create ad hoc technology applications, leading to digital impairment in both the conventional and non-conventional economies.

Perceived Benefits and Entrepreneurial Openness

The study findings also show a positive inclination towards digital technology among township entrepreneurs, despite infrastructural and institutional pressures. Small business owners do not hesitate to use digital tools when they feel they can lead to measurable business advantages, including customer retention, optimisation, and marketing efficiency (Bingwa, 2024). The results also highlighted the increased interest in digital learning, particularly after the COVID-19 pandemic, when online platforms became central to maintaining continuity in businesses (Dos Santos & Duffett, 2021). The urge to embrace technology, however, is often hindered by a systematic inability to access training services, technical assistance, and subsidised infrastructure (Tshabalala & Beharry-Ramraj, 2021). This suggests that the underutilisation of digital technology by township small businesses today is not due to malicious resistance, but instead to the attitude of neglect and socio-economic constraints that exist in such township environments. Nevertheless, the attitude towards entrepreneurship is flexible and open to change, indicating the possibility of change when relevant supporting mechanisms are implemented.

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5. Discussion

Digital technologies have significantly improved business performance, particularly in marketing activities, customer communication, and transaction processing (Bvuma & Marnewick, 2020; Hongoro et al., 2022; Madzvamuse et al., 2024; Matsepe & Van der Lingen, 2022). Social media platforms and mobile POS systems have become highly popular among township small businesses due to their affordability, ease of use and availability, which leads to profitability of the business (Muchineripi et al., 2025; Tshabalala & Beharry-Ramraj, 2021). Such advantages align with other international research, such as that of Malatji (2022), which demonstrated that mobile applications enabled small businesses operating in low-income environments to scale up, expedite the transaction process, and gain customer confidence. The use of the TAM also supports this perception, in which the usefulness and ease of use are crucial determinants of whether township small businesses adopt the digital technology or not (Almawash & Saleh, 2024).

Nonetheless, the study findings indicate that the digital technology adoption has been partial, inconsistent and narrowly functional in township small businesses. Most small businesses in South African townships selectively utilise digital technology for communication and payments, but not in core business operations, such as inventory management, accounting, or data analytics (Achieng & Malatji, 2022; Udimal & Biyase, 2021). The same trend was observed in most developing economies, with small businesses in the township economy being compelled to adopt technology solely because they need to, but lacking the systematic support to continue or grow in digital technology strategies (Gavaza, 2025; Matsepe & Van der Lingen, 2022). The hybrid approach adopted by township small businesses, which involves supplementing analogue systems with digital technology, is an interim solution; however, in many cases, it is a long-term survival strategy, especially in township environments where a formally established ecosystem of business support is lacking.

In addition, the study findings highlighted the lack of policy and institutional structures adapted to the digitalisation of small businesses in townships. Although the National Development Plan is working towards digitising small companies, the vast number of unregistered small businesses in townships receives little attention. This policy blind spot means that a township entrepreneur is left to informally learn and experiment with digitalisation, as Bvuma and Marnewick (2020) contend. The selective support strengthens the registered business, but on the other hand, creates structural inequality as townships' small businesses are left unattended. Similar results were described by Bingwa (2024), who emphasised that the digital consumption of small businesses in KwaZulu-Natal was not substantially supported by consistent institutional policy errors that led to the ad hoc, temporary use of technology.

Nonetheless, the obstacles mentioned above are surpassed by an entrepreneurial receptiveness to digital technology transformation. When the benefits of using digital technology are evident, township small business owners are always willing to adopt them, provided that the tool is culturally and contextually relevant (Kelly et al., 2022). It is an unexploited business agility that supports inclusive digitalisation growth. Yet, to make this potential a reality, interventions need not be limited to infrastructure and providing access to devices. Scholars argue that there should be localised training funds, subsidised information, and constant technical assistance tailored to the unique realities of township small businesses (Bvuma & Marnewick, 2020; Tshabalala & Beharry-Ramraj, 2021).

When synthesising the study findings, it becomes evident that the issue is not one of unwillingness or unawareness among small business entrepreneurs. Instead, what is missing are the enabling conditions to scale and sustain the use of digital technology: infrastructure, education, finance, and policy coherence. Therefore, digital exclusion in township business settings is a concern for technology, governance, equity, and development. This means that the road to inclusive digital technology adoption should be interdisciplinary and integrate technological, educational, economic, and political approaches, so that township businesses do not operate as mere consumers of technology but as agents involved in the digital technology economy.

Implications for Policy

Intensifying policy interventions in township small businesses is desirable in an inclusive approach that is geared towards small business development. Though frameworks like SA Connect and the National

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Development Plan recognise the issue of digital technology inclusion, to a large extent, they do not take into account the realities of township small businesses (Department of Small Business Development, 2023). More attention should be paid to the establishment of township-specific programs to support the digitalisation of technology that are aimed not only at internet connection. Such packages must feature a subsidised data and equipment package for small businesses, incentives to adapt to operational technologies, and a simplified regulatory track that allows township businesses to transform themselves over time. Furthermore, the local government can significantly contribute to solving the problem by creating digital hubs in the townships, where entrepreneurs can access common and shared technological resources, mentors, and technical assistance at minimal or no cost.

Implications for Practice

Practically, NGOs, business development agencies and other players in the private sector must turn their attention towards capacity-building projects, developed to suit the township environment. Training sessions must be made modular, language-supportive, and in a form that is easily accessible through mobile workshops, community centres, and peer learning groups. Additionally, financial institutions play a crucial role in facilitating greater adoption. Coordinating on products: these actors can assist in filling these affordability gaps by designing financial products that specifically target township small businesses, such as microloans to invest in technologies or waivers of transaction fees via mobile payments. Additionally, collaboration with digital service providers, coupled with township business associations, can be leveraged to build more trust and facilitate faster uptake, thanks to the existing structures within communities that promote credibility and reach.

6. Recommendations

Policy and Government Interventions

The local government should subsidise the most important digital technologies by introducing the Township Digital Empowerment Fund (TDEF), which will cover the cost of mobile POS systems, cost-effective smartphones, and basic inventory software. The specified form of funding will directly eliminate affordability issues that restrain the use of digital technologies in township setups. Additionally, a Township Digital Adoption Policy Framework is to be designed to outline tangible implementation strategies for expanding digital infrastructure, enhancing robust internet connections, and providing tax waivers to small businesses that adopt proven best digital models. Moreover, local and provincial governments should also incorporate digital literacy services into their existing township economic development plans. By mainstreaming technology skills into the established activities of comprehensive small business support programmes, township entrepreneurs are empowered to adopt and continue using digital technology applications, thereby ensuring inclusive economic growth.

Training and Capacity-Building Programs

Higher education institutions, local development agencies, and NGOs should design and offer modular training at the community level, including skills development such as mobile marketing, digital payments, and basic financial management, utilising digital tools. These programs are to be held in locally spoken languages and in convenient community centres, which include educational buildings and community halls, to be more approachable to a maximum number of people. Furthermore, a digital mentorship program should be implemented, where hand-picked digital champions (entrepreneurs who managed to implement technology into their small businesses) would mentor and advise their fellow entrepreneurs. This strategy recognises the value of society and the importance of practical, experience-oriented learning. Additionally, learning can also be boosted through the presence of collaborative bootcamps organised in partnership with the private sector (e.g., technology companies and telecom providers). All digital technology adoption bootcamps must be practical and applied in real life, so that township entrepreneurs can practice the skills and not just theoretical knowledge.

Private Sector and Fintech Support

The technology providers and fintech corporations should design customised digital solutions to suit the township's small businesses. The key features that should be offered in these solutions include basic operations such as cost control and inventory tracking, rather than highly complex, enterprise-based functions that might be out of reach for small township businesses. Additionally, telecom providers have the opportunity to offer

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discounted or flexible data plans that include small business applications. Meanwhile, banks and fintech companies can introduce a structure where, under certain conditions, transaction fees are reduced or a cashback is offered on online transactions. These economic reasons can reduce the cost barrier and increase regular visits to digital platforms. There should be collaborative, co-branded outreach efforts with fintech companies, local influencers, and township small business associations, which will be utilised as an outreach tool to demonstrate successful use cases, demystify technology, and encourage community buy-in.

Stakeholder Collaboration

Most of these suggestions require joint cross-sector efforts to be implemented effectively. The task force should be established at both the municipal and provincial levels and should comprise representatives from the government, non-governmental organisations, the business sector, academic institutions, and township small business associations. The responsibility of this task force would entail aligning strategies, tracking the progress of technology adoption, and adjusting interventions based on community feedback. To maintain accountability, common monitoring and evaluation systems must be established, allowing all stakeholders to track the levels of digital technology adoption and business-level outcomes, and share lessons learnt continuously. Lastly, a pilot and scale-up strategy should be implemented. Stakeholders can also experiment with integrated digital support models in selected townships and replicate the models in other regions, depending on the evidence and success rate.

This paper is limited by its dependency on secondary literature, which may vary in terms of methodology stringency, context specificity, and representativeness. The analysis combined findings from different township contexts, but was unable to explain regional, sectoral, or demographic differences in detail. In future research studies, a quantitative or mixed approach to examining the level and effect of technology adoption in the townships' small businesses should be adopted. Future research studies are also advised to pay more attention to the assessment of not only the adoption but also the use of technology outcomes. These involve examining the long-term impact of digital tools on revenue growth, employment creation, efficiency, and market access.

Conclusion

The study has examined the use of technology in township small businesses in South Africa, drawing on a systematic review of academic and policy literature. The evidence shows that the interest in and perceived usefulness of digital tools are evident, although their adoption is not yet complete. As the research findings indicate, their use is partial, with some structural barriers, poor infrastructure, low digital literacy, and inadequate institutional support. The study highlighted the need to stop treating digital adoption as a mere technical challenge, but rather as a socio-economic development agenda that should be integrative and context-sensitive in its approaches. The reduction of the digital divide in township economies implies that stakeholders will be involved in multi-pronged activities, which comprise community-based training programmes, financial investment in infrastructure, and the establishment of coherent policies that acknowledge and assist township small businesses. Specifically, community engagement through digital technology literacy and entrepreneurship services offered by higher education institutions can play a crucial role, as they stand at the intersection of local knowledge and national policies.

Additionally, campaigns on affordable and relevant technologies can enable township entrepreneurs to use the appropriate tools that fit their small business model and limitations. The study concludes that small businesses in townships are not technology-resistant but are instead locked out through systematic exclusions. Tapping into their already open yet resilient outlook by developing well-informed interventions, both economically and socially, can unlock immense potential, making a substantial contribution to South Africa's overall digitalisation and economic convergence targets.

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ANALYSIS OF REGIONAL DISPARITIES IN HUMAN CAPITAL IN EUROPEAN UNION COUNTRIES*

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Abstract. Human capital is one of the key factors for sustainable economic growth and social development. In the European Union, which is characterized by relatively significant differences between individual member states, the analysis of human capital and the determinants that influence it plays an important role in understanding regional disparities in quality of life and economic performance. The aim of this article is to analyse the level of human capital in EU countries using the Human Development Index, identify its regional disparities, and assess the extent to which spending on key areas contributes to HDI variability between countries. At the same time, we also focused on assessing the importance of non-expenditure factors that may influence the level of human capital in order to provide a more comprehensive view of the issue. The analysis is based on Eurostat and United Nations Development Programme databases for the period 2014–2023. A one-factor analysis of variance supplemented by Tukey's HSD test was used to determine the existence of regional differences in HDI. We used the Mann-Whitney U test to determine whether the identified differences were the result of unequal spending in three key areas affecting human capital (health, education, and research and development). Finally, we used multiple regression and correlation analysis to identify other (non-expenditure) factors that could be significant determinants of human capital. We found that HDI values are higher in northern and western European countries than in southern and eastern European countries. There is a statistically significant difference in HDI between countries with higher and lower spending on health care and research and development, respectively, but there is no statistically significant difference in HDI between countries with lower and higher spending on education. Among non-expenditure factors, average life expectancy at birth and the proportion of the population with tertiary education appear to be significant determinants of HDI. Other variables analysed, despite a positive correlation with HDI, did not show a statistically significant impact.

Keywords: European Union; human capital; human development; Human Development Index; regional disparities

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1. Introduction

Extensive research in the field of human capital and human development stems from the importance of the human factor in achieving economic growth and development of society (Gruzina et al., 2021, Ziberi et al., 2022, Sultana et al., 2022, Ramallari & Velaj, 2023, Carillo, 2024, Uddin et al., 2025 and others). Human capital, as one of the most important sources of economic growth, includes the knowledge, skills, health and abilities of individuals, which directly affect productivity and, consequently, the quality of life (Evanoff, 2021, Zahra Al-Hujaimi & Al-Hashemi, 2021, Cappelli et al., 2023, Chereyeva et al., 2025 and others). Within the European

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Union, which is characterized by differences in the historical, economic and social development of individual countries, the analysis of human capital is key to understanding differences in economic levels and quality of life. A wide range of indicators is used to assess the level of human capital and human development, including the Human Development Index. This index includes indicators of education, life expectancy and living standards, thus providing a comprehensive view of the development and quality of life of the population.

This article focuses on assessing the level of human capital in the EU Member States using the Human Development Index, identifying regional disparities, with particular attention paid to the key factors that shape human capital and assessing how they contribute to these differences. The aim of the article is to provide a deeper and more comprehensive view of the issue of human capital in the four basic geographical areas (regions) of Europe: Northern, Western, Southern and Eastern Europe.

To determine the existence of regional differences in HDI, a one-way analysis of variance was used, which was supplemented by Turkey's HSD test to refine the results. To verify whether the differences in HDI between the studied groups of countries can be at least partially influenced by unequal spending in three important areas (health, education, research and development), the Mann-Whitney U test was used in the next part of the analysis. In addition, we also tried to identify non-expenditure factors that could have an impact on the level of human capital through multiple regression analysis and correlation analysis. Despite the importance of HDI as an indicator of human capital development, there are only a limited number of studies that systematically examine regional differences in HDI within the EU and at the same time analyse the impact of expenditure factors on these differences (Laskowska & Dańska-Borsiak, 2016; Hippe, 2020; Ederer et al., 2020). This research therefore responds to the need for a more comprehensive approach to understanding, in particular, the expenditure determinants of human capital in the European context but also complements them with non-expenditure determinants at the pan-European level. The research uses a combination of several statistical methods, which allows for a deeper assessment of the relationships between the HDI and its individual determinants. In addition, its results can provide an incentive for the creation of public policies, especially in the areas of investment in health, research and development, as well as education, especially given their different levels of impact on the HDI. The finding that education expenditure does not show a statistically significant impact on the HDI also opens space for a discussion on the effectiveness of public resources in this area and suggests the need to re-examine existing theoretical models that assume the existence of a linear relationship between the amount of expenditure affecting human capital and its level.

The structure of the article is as follows: in the first part we will focus on a summary of the theoretical foundations of the research issue, in the next part we will explain the research methodology. In the third part we will present the research results, in the fourth part we will evaluate the achieved results in the context of the findings of other authors dealing with the given issue as part of the discussion. The conclusion contains a summary of the most important results and findings of the article.

2. Theoretical background

Human capital is considered a key driver of the knowledge economy, playing a fundamental role in its development. For this reason, to ensure the progress of the economy and society, it is essential to pay attention to the development of human capital by increasing investments in human capital (Xu & Li, 2020). According to Kucharčíková et al. (2024), people as representatives of human capital are carriers of knowledge, ideas and experiences that contribute to increasing the performance and competitiveness of society. According to Harper (2025), human capital is perceived as a set of characteristics and abilities that include knowledge, talent, skills, intelligence and education. These aspects are individually and collectively controlled and owned by individuals in the population and are of importance for the economy. Angrist et al. (2021) understand human capital as resources associated with the knowledge and skills of individuals. Similarly, Cappelli et al. (2023) define human capital as the set of knowledge and skills that individuals accumulate over time, which results in an impact on labour productivity and innovative capacity, thus considering human capital as one of the most important determinants of economic growth. A detailed description of human capital is offered in his study by Evanoff (2021), who characterizes human capital as a set of habits, knowledge, and social and personal characteristics, including creativity, that include the ability to perform work and create economic value. It consists of the

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knowledge, skills, and health that people invest in and accumulate throughout their lives to fulfil their potential as productive members of society. Similarly, Zahra Al-Hujaimi & Al-Hashemi (2021) have elaborated on the nature of human capital, referring to it as a general concept of knowledge and skills contained in people that play an important role in determining labour productivity and their ability to absorb new knowledge and master new technologies. Furthermore, human capital is defined as an intangible asset or quality that is not included in the balance sheet of a company, and which can be categorized as the economic value of a worker's experience and skills, and includes assets such as education, training, intelligence, skills, health, and other things that employers value, such as loyalty and punctuality. Turgel & Fazylzhan (2023) understand human capital as a set of skills, abilities, and knowledge acquired through investments in education, health, and continuing education, which are used to generate profit for both individuals and society.

While the theoretical framework of human capital emphasizes its universal importance, empirical studies point to significant regional differences in its level. Hippe (2020) draws attention to the fact that there are regional inequalities around human capital in European countries, which are influenced by historical development, geographical location, but also the orientation of government policy. Following this, in line with the aim of the article, in the empirical part we focus on testing hypothesis H1, which assumes that there is a statistically significant difference in the average HDI value between individual EU regions.

According to Matei and Ceche (2018), human capital consists of those abilities of individuals that are characteristic of them and remain the same in any social environment and can be used in the labour market in exchange for economic resources of any kind. In practice, human capital, according to the authors, consists of educational capital (skills acquired by individuals in the process of education, but also outside it) and biological capital (physical abilities of individuals, synthesized most often through health status). Given the above, investments in human capital can take various forms, with investments in school education, vocational training in the workplace and healthcare among the basic ones (Kipyego, 2023). The investments are characterized by their constant and long-term nature of investment and are inextricably linked to the individual who acquires them in the form of knowledge and skills, which contributes to increasing professional and professional skills, and subsequently to increasing production and productivity growth. Kipyego (2023) refers to this phenomenon as an internal effect resulting from investments in human capital. In addition, he also mentions an external effect, since increasing the productivity of one employee also positively affects the efficiency of other workers in the company.

Education and health are therefore considered the most important investments in human capital, according to Shafud (2020). Higher education and better health enable growth in labour productivity, production growth, and economic growth. As Chereyeva et al. (2025) state, investments in human capital help increase labour productivity, improve the level of education and health of the population, as well as support innovative development and improve the quality of life. Based on this, Turgel & Fazylzhan (2023) consider healthcare facilities, educational and scientific institutions, and continuing education centres as sources of human capital assets. Also, according to Erasmus (2021), the key elements of human capital development are based on investments in the education and health sectors. On the one hand, investment in education is a tool that creates new skills, knowledge and incentives that drive economic expansion by increasing the skill of individuals and creating a productive economy. Thus, education spending creates new technologies, inventions and innovations that lead to wealth creation and human capital development. On the other hand, health in old age reflects a state of complete well-being that leads to a competent workforce and improves human capital development through the acquisition of skills and knowledge. Similarly, Bassey et al. (2023) based on human capital research in Nigeria states that investment in education and health enhances human capital development in developing countries. The fact that sustainable economic growth cannot be achieved without human capital development is stated by Olawumi (2020), recommending increased spending on education and health to improve the quality of life, material well-being of workers and life expectancy for the sake of higher productivity. As Gruzina et al. (2021) point out, the efficiency of human capital investments is usually determined by the ratio of costs to economic results, or rather, actual results with expectations. A quantitative assessment of the social efficiency of human capital investments is measured by the contribution to economic growth, which should be reflected in GDP growth.

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Healthcare plays an important role in the quality of human capital. Higher spending on healthcare increases the productivity of human capital, as healthier individuals can work more efficiently, including in physical and mental stress (Raghupathi & Raghupathi, 2020). As Zarulli et al. (2021) argue, increasing healthcare spending is essential to achieving life expectancy growth, but more efficient use of resources can help countries improve their life expectancy even without increasing spending. Currently inefficient countries could benefit the most from spending reorganization, as the example of similar countries shows that higher levels of life expectancy at birth are achievable. Similarly, Ataklı Yavuz & Yilmaztürk (2023) state that societies that allocate sufficient resources to health tend to have higher quality of life and better health status. However, they point out the importance of efficient management of health spending and allocation of resources to the right areas. They suggest developing balanced and effective policies to ensure the sustainability of health systems and provide equitable health services to all segments of society. Since several authors point to the key role of health in the formation and development of human capital, in the empirical part we will focus on testing the hypothesis H2 that there is a statistically significant difference in the HDI value between groups of countries differentiated by the level of health spending.

Within the framework of human capital research and its development, most authors focus on clarifying the importance of education and its impact on the level of human capital. Garanin (2022) considers education to be the basis of human capital, because human capital is embodied in the knowledge, skills and abilities that are the result of education. Naros & Simionescu (2019) recall that education plays an important role in adapting human resources to the dynamic demands of the labour market and provides more options for choosing a better job.

Education is essential for economic growth and profitability because, according to Ramallari & Velaj (2023), it increases efficiency and helps the economy advance in the development process, which is a prerequisite for long-term development. As Coman et al. (2022) recall, education is the main engine of economic growth, and the education system must be organized in such a way that it prepares individuals to perform professions that may not even exist at the time of study. In addition, they state that public policies should improve the quality of general education and support lifelong learning programs for the adult population to ensure an adaptable and competitive workforce. In the above context, investing in education, according to Ziberi et al. (2022), means first and foremost investing in human resources, i.e. creating a skilled workforce that will influence the creation of innovations, increase productivity and wages, reduce the requirements for the state to finance various social programs, and increase the state budget through the accumulation of taxes, which will subsequently have a positive impact on the country's economic growth. In a similar vein, Okerekeoti (2022) expressed himself, stating that spending on education contributes to the development of human capital, which can lead to a trained workforce that can increase the productivity of both physical and human resources and subsequently lead to higher economic growth. Of course, higher education also has a positive impact on the standard of living of the individual, because, as Guijarro-Garvi et al. (2022), educated individuals earn greater monetary returns, obtain better-paid jobs, which reduces their risk of material deprivation and contributes to a higher level of subjective well-being. Given the essential importance of education for improving the quality of human resources and stimulating economic development, Oktavianty (2024) emphasizes the need for public financing of education as a fundamental element of long-term economic progress and improving personal well-being. Government spending on education can be, according to Tabar et al. (2017), an effective factor in promoting and acquiring knowledge, improving education and strengthening the spirit of innovation and originality in the community, and increasing the level of education of people in society represents an increase in the human capital of a given country, which leads to improved efficiency, enhanced production capacity and economic growth. Zogjani et al. (2024) based on research in Kosovo recommends an efficient allocation of education spending and aligning it with broader economic objectives to maximize growth potential and support economic development. Coronel and Díaz-Roldán (2024) examining the impact of public spending on education, productivity, wages and growth in the EU found that productivity growth is mainly contributed by spending on research and development in education and employment in sectors with high technological content, where a high level of skills is needed. They point out the need to use resources efficiently, which requires a distinction between the quantitative and qualitative dimensions of education provision. Education financing can be considered efficient if it leads to an increase in productivity. Based on the importance attributed to investment in education for human capital development, the empirical part focuses on testing hypothesis H3, that there is a statistically significant difference in the HDI value between countries differentiated by the amount of education spending.

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Several authors link the importance of education for the growth of human capital not only with healthcare, but also with the development of the digital economy, with innovation and research. As Patel and Annapoorna (2019) state, the growing dependence of industry on sophisticated capacities has significantly increased the importance of education for increasing the availability of human capital. The product of an educated mind is societal and global progress, which increasingly depends on research, invention, innovation and adaptation. Simmons (2024) states that education plays a key role in strengthening human capital and creating innovation, which in turn contributes to the economic prosperity of the country. For this reason, policymakers should prioritize investments in education to develop human capital and innovation, which would subsequently facilitate economic development.

Based on the results of their research, Kousar et al. (2023) recommend that the Pakistani government allocate more funds from its budget to health, education and social protection programs in order to increase its human capital, as these are the areas that have a positive and significant relationship with human capital in terms of primary, secondary and tertiary education attainment and life expectancy at birth.

Yu et al. (2023) found that there is a strong relationship between education expenditure, human capital development and innovation in science and technology, as education expenditure contributes not only to socio-economic development but also to the accumulation of human capital and progress in scientific and technological innovation. They conclude that the accumulation of human capital can accelerate the growth of scientific and technological innovation and stimulate economic growth, if education expenditure is increased and the quality of education is improved. According to them, increasing education spending can not only increase the innovative capacity of the educated, but also strengthen their ability to adopt and apply new technologies, leading to the transformation and transfer of knowledge, making education spending an effective means of supporting innovation in science and technology.

Science and progress are also highlighted as key factors influencing the formation of human capital by Gruzina et al. (2021). They state that economic growth in modern society is driven by ubiquitous innovations at all stages of its reproductive process. The generator and consumer of all new ideas is represented by a person (citizen and customer), who is also a highly qualified employee with up-to-date knowledge that needs to be constantly updated and supplemented throughout his or her life, as well as real-life experience. In their study, Diakodimitriou et al. (2025) found that education spending significantly affects economic growth, identifying R&D spending as the main channel through which this occurs. According to them, strategic allocation of funds in education, especially in conjunction with R&D, should strengthen economic growth and resilience, therefore, policymakers should support innovation in supporting tertiary education, funding research programs or other areas of education that are related to R&D. They explain this by saying that to sustain economic growth and support innovation, an education policy that ensures a skilled workforce that can fully exploit advances in R&D is essential. According to Paula & Silva (2021), it is important to invest in R&D, as there is a positive impact of R&D investment on national development, which is mediated by the total number of patent applications in a country. Patent applications are often considered one of the key factors in the development of technological innovation, but also in the overall economic development of countries (Leogrande et al., 2022). As Diebolt & Hippe (2019) show, human capital is the most important historical factor related to current patent applications per capita and current GDP per capita. Newer EU regions generally have lower patents per capita than the “old” Member States, and the same is true for GDP per capita.

The relationship between human capital and science and research is two-way. On the one hand, an increase in the inflow of human capital causes firms to produce more patents and improve the quality of innovations (Yang et al., 2022). On the other hand, higher spending on science and research contributes to the development of human capital, which in turn contributes to the innovation of the enterprise. Based on the above, it can be concluded that the increase in the density of human capital in research is associated with a significant increase in publications and patents, which indicates that countries that invest relatively more in personnel working in research and development produce more research outputs in the form of patents and publications (Ayan et al., 2023). Since, in addition to education and health, many authors claim that investment in research and development also significantly affects the level of human capital, in the empirical part of the research we will

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also test hypothesis H4, that there is a statistically significant difference in HDI between groups of countries differentiated by the level of research and development expenditure.

Education, health, science and research are fundamental factors influencing the level of human capital in the sense of the above. However, the measurement of the level of human capital itself is debatable, because there are several approaches that focus on different areas and characteristics of human capital. Turgel & Fazylzhan (2023) identified four main categories of approaches in human capital research in their research: investment approach, human capital as a fund (reserve), human capital as a factor of production and human capital as an asset. The investment approach allows us to assess the concept of "human capital" through investments in education, health and further education, which after a certain time can bring dividends to a person in the form of wages. The second approach, the approach to human capital as a "fund", examines it as a "reserve" of skills, abilities and human capabilities that a person acquires during his life. The approach to human capital as a factor of production pays special attention to human competencies, which are the main driving force of production and the economy. The latter approach considers the physical and non-physical assets that constitute human capital itself.

As Matei & Ceche (2018) state, the process of assessing human capital is generally very complex. It should consider and include the characteristics of the impact and classification of human capital at a general or specific societal level. The diversity of measurement methods suggests the need to introduce a unified approach, since comparing the results of different indices within and between countries is not possible (Armstrong & Taylor, 2020).

In connection with the investment approach to measuring human capital, the Human Development Index indicator is often used in research. Patel & Annapoorna, (2019) examined the impact of education expenditure on human resource development in India, assessing the relationship between education expenditure and India's ranking in the Human Development Index. Okafor et al. (2017) used HDI to examine the impact of government expenditure on human capital development in Nigeria. Edeme & Nkalu (2019) also conducted research on the relationship between public expenditure and human capital using HDI in the context of Nigeria. Maharda & Aulia (2020) conducted their research on the relationship between government expenditure on education and health and HDI in the context of Indonesia. The relationship between human development (measured by HDI) and health expenditure in 25 OECD countries between 2003-2019 was investigated by Ataklı Yavuz & Yilmaztürk (2023). They found that increased investment in health (whether by the public sector or households themselves) contributes to human development in these countries. Although most of the studies mentioned have shown a positive relationship between human capital expenditure and the Human Development Index, the relationship was not confirmed in the study by Okafor et al. (2017).

3. Research objective and methodology

The aim of the article is to analyse the level of human capital in the European Union countries through the Human Development Index, identify its regional disparities and assess the extent to which the level of expenditure on key areas contributes to the variability of the HDI between countries. At the same time, the article focuses on assessing the importance of non-expenditure factors that may affect the level of human capital, to provide a more comprehensive view of the issue. The analysis was carried out for the period 2014-2023 and was based on statistical data from Eurostat and the United Nations Development Programme. We used the Human Development Index (HDI) to express the level of human capital, as it represents a relatively comprehensive and internationally recognized indicator that captures the most important dimensions affecting human capital.

Using one-way analysis of variance (ANOVA), we investigated whether there are regional differences in HDI in EU countries. We chose this method because it is a frequently used method for comparing means across groups (Montgomery, 2017). Countries were divided into four groups for this analysis, in accordance with geographical location and historical and socio-economic conditions, as well as their division in some other studies (Hudzelyak, 2024; Stojanovic, Zakic, 2024; Malinauskaite et al., 2024; Pagiotti et al., 2024):

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- Western European countries (Belgium, France, Netherlands, Luxembourg, Germany, Austria, Ireland)
- Northern European countries (Sweden, Finland, Denmark)
- Southern European countries (Portugal, Spain, Italy, Greece, Malta, Cyprus)
- Eastern European countries (Slovakia, Czech Republic, Hungary, Poland, Estonia, Lithuania, Latvia, Bulgaria, Romania, Slovenia, Croatia).
-

To determine which regions, have statistically significant differences, Tukey's HSD test was used, which is suitable for comparing all pairs of groups and is often used as a complement to ANOVA in calculations (Montgomery, 2017). We used the formula:

$$HSD = q_{crit} * \sqrt{\frac{MS_{within}}{n_{ef}}}$$

where:
q_{crit} – table value
MS_{within} – ANOVA output
n_{ef} – effective group size $\frac{2}{\frac{1}{n_1}+\frac{1}{n_2}}$

If HSD < the difference between the respective groups, the result is statistically significant. Conversely, if HSD > the difference between the respective groups, the result is not statistically significant.

To examine whether the differences in HDI between these groups of countries are at least partially determined by inequalities in the volume of expenditures in three key areas (health, education, research and development), the non-parametric Mann-Whitney U test was used in the next section. According to Nachar (2008), this test is one of the most powerful non-parametric tests and there is a good probability that it will provide statistically significant results. The amount of expenditure was assessed based on the share of the respective expenditure group in GDP. Countries were divided into two groups for each expenditure category – countries with below-average and above-average expenditure, and the average HDI level for the years 2014-2023 in these groups was analysed. We used the formulas (1,2):

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \quad (1)$$
$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2 \quad (2)$$

where:
n_1 n_2 – sizes of two groups
R_1 R_2 – sum of the order of values of the first and second groups.

Given that the amount of expenditure itself may not automatically correlate with the quality and efficiency of its use, and therefore with the real development of human capital, we also conducted a multiple regression analysis, in which, in addition to the expenditure variables, we also included three outcome indicators (average life expectancy at birth, share of the population with tertiary education, number of patent applications per million inhabitants), which we assumed could be significant determinants of HDI. We used the formula (3):

$$y_j = b_0 + b_1 x_j + \ldots . b_n x_n + \mathcal{E} \quad (3)$$

To supplement and deepen the interpretation of the results of the regression analysis, we also conducted a correlation analysis, the aim of which was to identify the basic relationships between individual variables, assess their strength and identify the existence of possible relationships between variables that were considered independent in the regression analysis. We based our analysis on the formula (4):

$$r_{xy} = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{\left[n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2\right]\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2\right]}} \quad (4)$$

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4. Results

As part of the assessment of the level of human capital in EU countries, we decided to identify whether there are differences in HDI between geographical regions (areas) of the EU. The aim of this part of the analysis was to determine whether there are statistically significant differences in the average HDI value between individual parts of Europe, which are characterized by different historical, economic and socio-political conditions. The countries were divided into four basic groups - Northern, Western, Southern and Eastern Europe. To verify whether there are statistically significant differences in HDI between these groups, a one-way analysis of variance (ANOVA) was used (Table 1). We tested the following hypothesis:

H1: There is a statistically significant difference in the average HDI value between individual EU regions.

Table 1. One-way analysis of variance of HDI in EU regions

Groups	*Count*	*Sum*	*Average*	*Variance*		
West	7	6.5338	0.9334	0.00026		
North	3	2.8474	0.94913	0.000021		
South	6	5.3702	0.89503	0.00018		
East	11	9.6111	0.87374	0.00079		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.02264	3	0.00755	16.652	5.71×10^{-6}	3.028
Within Groups	0.01042	23	0.00045			
Total	0.03307	26				

Source: UNDP, own calculations

The analysis was performed at a significance level of $\alpha = 0.05$. The calculated value of the test statistic F=16.652 significantly exceeds the critical value F crit = 3.028. The p-value found of 0.0000057 was very low. Based on these results, we accept H1, which states that there is a statistically significant difference in the average HDI value between the individual regions of the EU. Thus, through a one-way analysis of variance, we found that the level of human development is not evenly distributed in the European Union. The average HDI values for the period 2014–2023 in the individual regions of the EU are shown in Figure 1.

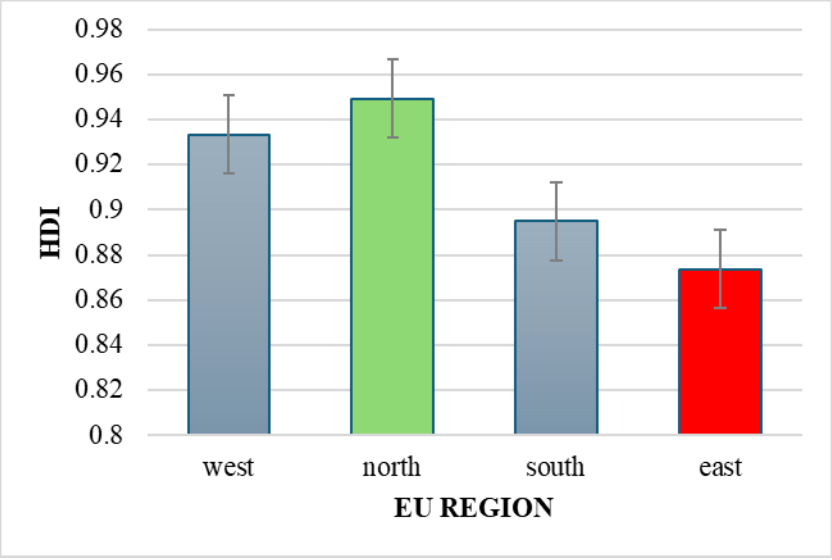


Figure 1. Average HDI values in the regions of the EU
Source: UNDP, own processing

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Western Europe was represented in the analysis by 7 countries (Belgium, France, Netherlands, Luxembourg, Germany, Austria, Ireland) with an average HDI of 0.9334, Northern Europe by 3 countries (Sweden, Finland, Denmark) with an average HDI of 0.9491, Southern Europe by 6 countries (Portugal, Spain, Italy, Greece, Malta, Cyprus) with an average HDI of 0.8950 and Central and Eastern Europe by 11 countries (Slovakia, Czech Republic, Hungary, Poland, Estonia, Lithuania, Latvia, Bulgaria, Romania, Slovenia, Croatia) with an average HDI of 0.8737. The highest average HDI values were thus recorded in the countries of Northern Europe, followed only very slightly by the countries of Western Europe, while lower values were found in the countries of Southern and especially Eastern Europe. This may reflect long-term differences in the economic and social levels of individual regions. Since we found that there are differences between individual EU regions, we decided to identify between which regions these differences are statistically significant (Table 2).

Table 2. Tukey's HSD test

Groups	Difference	n_1	n_2	Effective sample size	Honestly significant difference	Statistical significance
West - North	0.0157	7	3	4.20	0.0406	no
West - South	0.0384	7	6	6.46	0.0327	yes
West - East	0.0597	7	11	8.56	0.0285	yes
North - South	0.0541	3	6	4.00	0.0416	yes
North - East	0.0754	3	11	4.71	0.0383	yes
East - South	0.0213	11	6	7.76	0.0299	no

Source: UNDP, own processing

Using the Tukey HSD test performed at a significance level of $\alpha = 0.05$, we identified which EU regions have statistically significant differences. The results show that the largest difference in average HDI (0.0754) was recorded between the countries of Northern and Eastern Europe. This value exceeded the statistical significance threshold of HSD = 0.0383, indicating the existence of a significant difference in the level of human development between the countries of the Northern and Eastern EU. Lower, but still statistically significant differences were also recorded between the countries of Western and Eastern Europe (0.0597 > 0.0285), Northern and Southern Europe (0.0541 > 0.0416), as well as between the countries of Western and Southern Europe (0.0384 > 0.0327). On the contrary, the difference between the western and northern regions of the EU was not statistically significant (0.0157 < 0.0406), which suggests that these two regions have a similar level of human development typical of advanced economies with long-term investments in education, healthcare and research. Interestingly, the difference between the eastern and southern EU countries was not statistically significant either (0.0213 < 0.0299), which indicates a relatively comparable level of HDI in these two groups of countries, despite differences in geographical location and historical development. The results of the Tukey HSD test thus confirmed that the best conditions for human capital development are in the countries of northern and western Europe, while the countries of eastern and southern EU achieve lower, but comparable HDI values. This suggests that despite the EU's efforts for gradual convergence, regional disparities in human capital still exist, which may result from several aspects.

Since the analysis showed that there are statistically significant differences in HDI between the EU regions, and that countries in the west and north of the EU perform better in terms of human development than countries in the south and east, we decided to investigate whether these differences can be explained, at least in part, by the different levels of expenditure on key areas (health, education, research and development) that affect human capital. To this end, we performed a series of Mann-Whitney U tests, which are suitable for comparing two independent groups when the groups have different numbers of data. We compared countries with higher spending (above the EU average) and lower spending (below the EU average) in terms of their HDI. We tested the following hypothesis:

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H2: There is a statistically significant difference in HDI between countries with higher and lower expenditure on health.

Table 3. Public expenditure on health – Mann-Whitney U test

Group 1	Group 2	U value	Critical value U (p <0,05)	Z-score	p-value	Statistical significance
EU countries with above-average healthcare expenditure	EU countries with below-average healthcare expenditure	32.5	50	2.81452	0.00496	yes

Source: Eurostat, own calculations

We investigated whether there is a statistically significant difference in the level of the Human Development Index between EU countries that spend above-average and below-average health care (Table 3). The analysis was carried out for the years 2014-2023, while the average value of health care expenditure for the entire period was calculated for each EU country. From these average values, an overall average value was then calculated, which made it possible to divide EU countries into two groups – countries with above-average and below-average public health care expenditure. These two groups of countries were then assigned HDI values. To test this hypothesis, we used the Mann–Whitney U test. The analysis was carried out at a significance level of $\alpha = 0.05$. The U value in this case was 32.5. The critical value of U at $p < 0.05$ is 50. $32.5 < 50$, indicating a statistically significant difference in HDI between countries with above-average and below-average spending. The result was also supported by the z-score = 2.81452, which means that the difference is approximately 2.8 standard deviations away from the expected U value. The result is also confirmed by the low p-value of 0.00496 < 0.05. Based on these results, we confirm H2, which assumed that there is a statistically significant difference in HDI between countries with higher and lower public spending on health. This finding may signal that investment in health can play an important role in human capital development. Higher investments in health can mean better access to health care, which can be reflected in increasing life expectancy, reduced morbidity, which is subsequently reflected in the HDI value. However, this statement is only generally valid, since even among countries with above-average health expenditure values, we find countries that also show below-average HDI values (Spain, Croatia or Italy), and conversely, among countries with below-average health expenditure values, we find countries that also show above-average human development values (Ireland, Luxembourg or Malta). These exceptions point to the fact that the amount of health expenditure is only one of several factors that can influence the HDI, or that it is not only the amount of expenditure that is important, but also its effective use. We tested the following hypothesis:

H3: There is a statistically significant difference in HDI between countries with higher and lower education expenditure.

Table 4. Public expenditure on education – Mann-Whitney U test

Group 1	Group 2	U value	Critical value U (p <0,05)	Z-score	p-value	Statistical significance
EU countries with above-average expenditure on education	EU countries with below-average expenditure on education	69.5	50	1.01905	0.30772	no

Source: Eurostat, own calculations

We proceeded similarly to public expenditure on health in the case of public expenditure on education (Table 4). We investigated whether there was a statistically significant difference in the HDI level between EU countries with above-average and below-average public expenditure on education. The subject of the analysis was data for the period 2014-2023 and the average value of expenditure for the given period was calculated for each EU country. The average values for individual member states were then used to calculate the overall

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average value, based on which we divided EU countries into countries with below-average public expenditure on education and countries with above-average public expenditure on education. The Mann–Whitney U test was used to test the hypothesis that there was a statistically significant difference in HDI between countries with higher and lower expenditure on education. The analysis was performed at a significance level of $\alpha = 0.05$. In this case, the calculated test statistic value U = 69.5 was higher than the critical value U = 50, indicating that there is no statistically significant difference between the groups. This finding is also confirmed by the low z-score = -1.01905, which is within the non-significance interval, and the statistical non-significance was also confirmed by the p-value 0.30772 > 0.05. Based on these results, we reject H3, which assumed that there is a statistically significant difference in HDI between countries with higher and lower public spending on education. Since it has been shown that higher public spending on education may not automatically lead to better human capital development, but education is generally considered one of the most important prerequisites for its development, it would be necessary to pay attention to other related aspects such as the quality of the education system in individual countries, the availability of education for different social groups, the connection of education with the labour market, etc. These factors can significantly influence the extent to which investments in education translate into improvements in human development in individual countries. We tested the following hypothesis:

H4: There is a statistically significant difference in HDI between countries with higher and lower R&D expenditures.

Table 5. R&D expenditures – Mann-Whitney U test

Group 1	Group 2	U value	Critical value U (p <0,05)	Z-score	p-value	Statistical significance
EU countries with above-average expenditure on R&D	EU countries with below-average expenditure on R&D	14.5	47	3.60229	0.00032	yes

Source: Eurostat, own calculations

As part of the analysis, we investigated whether countries with higher R&D expenditure as a share of GDP achieve significantly higher HDI compared to countries with lower expenditure (Table 5). As in previous cases, we examined data for the period 2014 to 2023, calculating the average amount of expenditure for each EU member state over the entire period. Based on the individual averages, we then determined an overall average for all EU countries. Accordingly, we divided the countries into two groups – those with below-average R&D expenditure and those with above-average expenditure. To test the hypothesis that there is a statistically significant difference in the human development index between these two groups of countries, we used the Mann–Whitney U test. The analysis was performed at a significance level of $\alpha = 0.05$. The calculated U value was 14.5, which is significantly lower than the critical value U = 47, indicating the existence of a statistically significant difference in HDI between countries with above-average and below-average R&D expenditures. The statistical significance of the result is also confirmed by the low p-value of 0.00032 < 0.05 and the z-score = -3.60229, which significantly exceeds the threshold of non-significance. Based on these results, we therefore confirm H1 that there is a statistically significant difference in HDI between the two groups of countries studied. The above finding suggests that R&D expenditures can significantly contribute to the development of human capital. R&D usually supports innovation, technological progress and productivity, which has the potential to positively affect the quality of life and the overall level of human development. However, we consider it necessary to emphasize again that this is a general trend that does not apply in some cases. Even some countries with lower spending in this area, such as Ireland or Luxembourg, achieve above-average levels of human development. On the other hand, Estonia spends above average on research and development but lags behind in human capital development. A quantitative increase in spending on research and development creates a favourable precondition for improving the HDI, but it does not guarantee its improvement. Human capital is determined by many other factors, and therefore attention should also be focused on other areas.

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Since we found out based on the previous analysis that education spending alone may not automatically lead to better human capital development, we decided to identify other factors through multiple regression analysis that could influence the level of human capital in EU countries. In addition to the expenditure indicators already used (government expenditure on health, government expenditure on education and expenditure on research and development), we also included in the analysis outcome variables that we believed could have an impact on human capital development (life expectancy at birth, share of the population with tertiary education and number of patent applications per million inhabitants). We chose these variables because of their ability to capture at least partially the qualitative aspects of human capital and the potential for innovation, which is often a more accurate indicator of the efficiency of expenditure than the volume of investment itself (Table 6). The main reference indicator remained the HDI in this extended analysis applied to the EU.

Table 6. Multiple regression analysis

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Statistical significance*
Intercept	0.4940	0.1036	4.7682	0.0001	yes
Public administration expenditure on healthcare	-0.0005	0.0044	-0.1060	0.9167	no
Public administration expenditure on education	-0.0021	0.0041	-0.5003	0.6223	no
Expenditure on research and development	0.0202	0.0076	2.6468	0.0155	yes
Life expectancy at birth	0.0043	0.0014	3.1019	0.0056	yes
Share of the population with tertiary education	0.0013	0.0006	2.1952	0.0401	yes
Number of patent applications per million inhabitants	0.0000	0.0000	1.0829	0.2917	no

Source: UNDP and Eurostat, own calculations

Based on the results of multiple regression analysis, it can be concluded that the regression model achieved a high degree of explained variability. The value of the coefficient of determination $R^2 = 0.8617$. This means that approximately 86% of the changes in HDI can be explained by the included variables (public expenditure on health, public expenditure on education, expenditure on research and development, average life expectancy at birth, proportion of the population with tertiary education, and number of patent applications per million inhabitants). Even after considering the number of predictors, the model explains a high degree of variability, as confirmed by Adjusted $R^2 = 0.8202$. Although some variables were not statistically significant, the model is statistically significant, as confirmed by the low Significance F value of 0.0000001.

The coefficient for variable healthcare expenditure is -0.00046, but it is not statistically significant (p-value = 0.9167). Therefore, within the selected model, it can be concluded that healthcare expenditure does not have a significant impact on HDI in the EU, although the Mann-Whitney U test confirmed that there is a statistically significant difference in HDI between countries with higher and lower healthcare expenditure. This discrepancy may indicate that the relationship between health expenditure and HDI is not linear, or that it is influenced by other factors that are not captured in the regression model but were detected by the non-parametric test. In the case of education and research and development expenditure, we find consistency between the Mann-Whitney U test and regression analysis. Based on p = 0.6223, education expenditure does not have a significant impact on HDI in EU countries, as has been previously demonstrated. On the contrary, for research and development expenditure, the coefficient = 0.02024 is positive and statistically significant (p = 0.0155), indicating that higher investment in research and development contributes to an increase in HDI. If we look at the outcome indicators, average life expectancy at birth, as one of the important indicators of the health status of the population, based on the results of the regression model, shows a positive and statistically significant impact on the HDI (coefficient = 0.00432; p = 0.0056). This means that an increase in average life expectancy is associated with an increase in HDI. Although education expenditure was not statistically significant, the outcome indicator for education – the proportion of the population with tertiary education – has a positive and statistically significant impact (coefficient = 0.00131; p = 0.0401) on the HDI. A higher proportion of the population with higher education increases the quality of the workforce, the innovative potential, and the country's ability to adapt to

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change, which contributes to increasing the level of human capital. However, the number of patent applications per million inhabitants is not statistically significant (p = 0.2917), meaning that patents cannot explain changes in HDI. However, this indicator shows considerable differences between countries and its importance could increase in connection with the development of an innovative knowledge economy.

The results of multiple regression analysis showed that several factors influence human capital development, but not all expenditures have a direct demonstrable impact on HDI. There may be several reasons for this. The cause may be their ineffective spending, mediated effects through other factors, possible multicollinearity between independent variables, but also the fact that the impact of some expenditures may not be immediately apparent, but only after a certain time lag. We supplemented these findings with a correlation analysis (Table 7).

Table 7. Correlation matrix

	HDI	*Health expenditure*	*Education expenditure*	*R&D expenditure*	*Life expectancy at birth*	*Share of population with tertiary education*	*Number of patent applications*
HDI	1.000						
Health expenditure	0.572	1.000					
Education expenditure	0.436	0.342	1.000				
R&D expenditure	0.768	0.811	0.568	1.000			
Life expectancy at birth	0.746	0.459	0.161	0.467	1.000		
Share of population with tertiary education	0.595	-0.021	0.424	0.286	0.409	1.000	
Number of patent applications	0.704	0.351	0.343	0.557	0.526	0.516	1.000

Source: UNDP and Eurostat, own calculations

The correlation matrix shows that there is a strong linear relationship between HDI and R&D expenditure, with a correlation coefficient of r = 0.768, indicating that countries with higher investment in R&D generally have a higher HDI. Another significant dependence was observed between HDI and average life expectancy (r = 0.746), which is not surprising, as this variable is directly included in the calculation of HDI itself. Given the results of the multiple regression analysis, according to which patent applications are not a significant predictor of HDI, the existence of a strong correlation between HDI and the number of patent applications (r = 0.704) is surprising. However, such a discrepancy between the results of correlation and regression analysis is a common phenomenon. The number of patent applications shows a relatively strong correlation with other independent variables included in the regression model, with research and development expenditure (r = 0.557) and the proportion of the population with tertiary education (r = 0.516). In the regression model, a significant part of the variability was explained by these variables, and as a result, the number of patent applications did not explain the additional variability of the HDI beyond what was already captured by other factors. Thus, the effect of these variable overlaps with other related variables in the model. We observed the weakest, albeit still positive, correlation with HDI in education spending (r = 0.436), which confirmed previous findings. However, it can be assumed that these expenditures contribute to a certain extent to the development of human capital, but rather indirectly, or with a time lag. Some correlations between independent variables were also noteworthy. For example, the correlation coefficient between research and development expenditure and health expenditure reached a value of r = 0.811. Such a close link between the two areas may reflect the fact that a large part of investment in research and development is related to healthcare. At the same time, such multicollinearity between independent variables could have affected the statistical significance of individual predictors in the regression model, as it is more difficult to interpret the individual contribution of each independent variable to

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the dependent variable when their effects overlap. As regards independent variables, research and development expenditure and education expenditure (r = 0.568) correlated more strongly, as well as research and development expenditure and the number of patent applications (r = 0.557), which points to the complex interdependence of these factors within countries' development policies.

5. Discussion

To express the level of human capital, we used the human development index, as it is internationally widespread and used in many studies (Patel & Annapoorna, 2019; Okafor et al., 2017; Edeme & Nkalu, 2019; Maharda & Aulia 2020; Bassey et al. 2023, and others). Nevertheless, it is sometimes subject to criticism, and some authors, such as Herre & Arriagada (2023), recommend considering the use of other indices, such as The Inequality-adjusted Human Development Index (IHDI), The Gender Development Index (GDI), or The Augmented Human Development Index (AHDI). First, we compared the differences in average HDI between EU countries. We found that countries in northern and western Europe have higher HDI values than countries in southern and eastern Europe, which is consistent with Hippe (2020), who argues that there are regional inequalities in human capital in European countries, influenced by historical developments, geographical location, and government policy orientation. Similarly, Laskowska & Dańska-Borsiak (2016) state that the highest level of human capital is typical of the richest regions of Western Europe, while the lowest level is found in the poorest countries that have only recently become members of the EU and in the countries of Southern Europe, including Greece.

In line with the literature (Railaite & Čiutienė, 2020; Nezhnikova 2020; Zarulli et al. 2021; Ataklı Yavuz & Yilmaztürk, 2023), it has been confirmed that public spending on health care and research and development has a positive impact on HDI. Mann-Whitney U tests revealed statistically significant differences in HDI between countries with higher and lower spending in these areas. According to Ederer et al. (2020), the level of investment in technological development and knowledge creation is too low, especially in Central and Eastern European countries, which is also reflected in low spending on areas such as healthcare, culture, and research and development in these countries compared to the rest of Europe. A remarkable but literature-supported (Linhartová, 2020; Okafor et al., 2017) finding was that spending on education did not show a statistically significant relationship with HDI. This may be because it is not always the volume of investment that is decisive, but rather its effectiveness (Zarulli et al., 2021), or that its impact is only felt after a certain time lag. This is also pointed out by Al Mamun et al. (2025), according to whom spending on education has a significant impact on HDI in the long term, which points to a time lag between investments and their real impact on development. In addition, the statistically insignificant relationship between education spending and HDI may also be related to the level of development of countries, because although in our case the impact of public spending on education on HDI appeared to be statistically insignificant, Bassey et al. (2023) found that government spending on education in Nigeria had a significant impact on human capital development as measured by HDI in both the short and long term.

Looking at the results of the regression and correlation analysis, it turned out that education spending did not show a statistically significant relationship with HDI and only achieved a lower correlation coefficient. On the contrary, the share of the population with tertiary education was a statistically significant predictor of HDI and had a higher correlation coefficient. This result contradicts the claim by Julistia et al. (2025) that spending on education affects the human development index, but that the final level of education has no impact on it. Another interesting variable was patent applications per capita, which, according to Diebolt & Hippe (2019) and Yang et al. (2022), are closely related to the historical accumulation of human capital as well as GDP per capita. This finding is consistent with our observation that countries with a higher human development index tend to have a higher number of patent applications, as evidenced by the relatively high correlation coefficient. However, when we included other relevant variables in the multiple regression analysis, patent applications did not prove to be a statistically significant predictor of HDI levels, probably due to multicollinearity and overlapping effects of independent variables. Given the economic situation in individual countries, this does not change the fact that the uneven distribution of human capital and innovation across regions leads to differences in development between regions (Jagodka & Snarska, 2023). This spatial inequality remains a challenge for the European Union, which has long sought convergence among member states in many areas, including education, innovation, and healthcare.

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Theoretical and practical implications: Our findings therefore show that the level of human capital does not depend solely on the volume of investment in key areas, but is also influenced by non-expenditure determinants, confirming the need for a more comprehensive approach to human capital issues. The research also confirms the existence of regional inequalities in human capital, supporting existing theories about the persistence of historical, economic, and socio-political differences between the countries of northern, southern, western, and eastern Europe. Since we have found that increasing expenditure in individual areas affecting the level of human capital may not ensure a higher level of human capital, policies aimed at its development should not only consider the amount of investment but also evaluate its effectiveness and redistribution to different sub-areas. Our findings may also provide impetus for regional policies within the EU, as despite the EU's efforts to achieve convergence in many areas, there are still more or less significant differences between member states. For this reason, it would be necessary, especially in areas with lower HDI, to re-evaluate the strategies for human capital development that have been applied so far.

6. Conclusions

The aim of this article was to analyse the level of human capital in European Union countries using the Human Development Index, identify regional disparities, and assess the extent to which spending on key areas contributes to HDI variability between countries. At the same time, we also focused on assessing the importance of selected non-expenditure determinants of human capital. The set objective was achieved. Through a one-factor analysis of variance, we found that there are statistically significant differences in HDI levels between individual EU regions. In northern and western European countries, the HDI is higher than in southern and eastern European countries. This was also confirmed by Tukey's HSD test, according to which there are statistically significant differences in the average HDI between the north and south, north and east, west and east, and west and south of the EU. These differences result from long-term historical, economic, and socio-political differences between individual regions. A series of Mann-Whitney U tests showed that there is a statistically significant difference in HDI between countries with higher and lower spending on healthcare and research and development, respectively. However, this finding is not absolute, as there were exceptions among countries, i.e., some countries with above-average expenditure had below-average HDI values, and conversely, other countries with below-average expenditure had above-average HDI values. This ambiguous effect of spending is further underscored by the fact that no statistically significant relationship has been found between spending on education and HDI levels. Since it has been shown that higher spending does not automatically lead to better human capital development, we decided to use multiple regression analysis to identify other factors that could influence the level of human capital. In addition to research and development expenditure, statistical significance was also demonstrated for average life expectancy at birth and the proportion of the population with tertiary education. Other variables analysed, despite their positive correlation with HDI, did not show a statistically significant impact, which is probably related to the problem of multicollinearity in the regression model.

Although we succeeded in achieving our goal of identifying regional differences in the level of human capital in EU countries and demonstrating that expenditure alone, without the simultaneous influence of other factors, may not ensure better conditions for human capital development, we consider it important to point out the possible limitations of the research carried out. Although the HDI is an internationally recognized index, its ability to express the level of human capital is limited, as it only considers three basic areas (average life expectancy, educational attainment, and per capita income), while neglecting qualitative determinants. For example, Raghuvanshi & Verma (2024) point to the need to supplement the HDI with alternative indices and qualitative assessments to ensure a deeper understanding of human development. Another limitation is that our analyses were based on average values for the period 2014–2023, which did not allow us to capture the dynamics of development and potential improvements or deteriorations, or responses to external shocks such as the Covid-19 pandemic. In addition, the statistical methods used (ANOVA, Mann-Whitney U test) allow us to test differences between groups, but do not prove a causal relationship between variables, because of which it cannot be convincingly argued that higher spending directly causes a higher HDI, but only that there is a certain relationship between them.

Based on the findings and identified limitations, further research should consider a more comprehensive approach to human capital assessment using multiple indicators, not just the HDI. Another challenge for future research could be to focus not only on the level of states, but also on regional differences within individual EU countries, as many differences in human development levels may be rooted in uneven regional development within individual member states. In addition, from a methodological point of view, it would be necessary in the future to pay increased attention to the problem of multicollinearity in the regression model and its mitigation, e.g., by removing highly correlated independent variables or other methods.

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THE GREEN VALUE CHAIN IN THE FURNITURE INDUSTRY: A CASE STUDY OF THE BEST PRACTICES OF KENNETH COBONPUE COMPANY IN THE PHILIPPINES*

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Abstract. This case study explores the green value chain best practices of Kenneth Cobonpue, a renowned Filipino industrial designer and the owner of Interior Crafts of the Islands, Inc., a furniture company. It has showrooms and offices in the Philippines, Germany, Portugal, and New York with a network of distributors in over 15 countries and 80 cities globally. In the company, there are more than 300 employees, including artisans who execute his designs using traditional weaving and knotting techniques and utilise natural materials to manufacture high-end furniture products. The research aimed to identify and examine the green value chain best practices of Kenneth Cobonpue, focusing on the sustainable green value chain practices, environmental impact, economic benefits, challenges and opportunities. Through qualitative research, including face-to-face interviews, site visits, and secondary data, the author showed how Kenneth Cobonpue integrates his green value chain strategies into his business model from design, to sourcing raw materials, production and distribution. Key findings highlight Kenneth Cobonpue's commitment to using natural and renewable materials, minimising waste, promoting energy efficiency, and supporting local craftsmanship. The opportunities and challenges of implementing green practices in the design sector are also covered in the study. It also offers insights for other designers and manufacturers aiming to enhance their environmental responsibility for business sustainability.

Keywords: value chain; green value chain; green business; environmental sustainability; business sustainability

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1. Introduction

In an era where environmental sustainability is becoming increasingly crucial, businesses across various industries are seeking ways to integrate green practices into their operations. This case study focuses on Kenneth Cobonpue, a prominent Filipino industrial designer known for his innovative and eco-friendly designs. The study aims to explore the green value chain best practices that Kenneth Cobonpue has implemented within his business in the Philippines.

The furniture industry is essential to a country's economic growth. It drives employment, industrial development, and international trade. Its contribution becomes even more significant when a country actively exports furniture, as this generates a wide range of economic benefits from job creation and livelihood support to increased export revenues, the growth of allied industries, and the promotion of local craftsmanship,

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innovation, sustainability, and regional development. In recent years, the Philippine furniture industry has gained global attention, where designers skillfully combine modern concepts with traditional materials. The well-known Cebu-based designer Kenneh Cobonpue exemplifies this approach, creating living-room pieces that feature fluid, almost organic forms traced in steel, rattan, bamboo, and abaca. Furniture buyers note that this fusion of the ultramodern and the earthy defines the Philippines' unique design identity and formula for success.

Cobonpue's design and manufacturing philosophy are fundamentally anchored in the principles of sustainability, which is why the researcher has chosen his company, which uses natural and renewable materials, specifically, rattan, wood, abaca, and bamboo. These materials demonstrate remarkable biodegradability, environmental friendliness, and compostability (Saba, 2017). By reducing production waste and empowering local artisans, Cobonpue has developed a business model that integrates environmental stewardship with socio-economic development. This study examines the specific strategies and practices that underpin Cobonpue's sustainable value chain, offering an in-depth analysis of how these initiatives contribute to both ecological preservation and community livelihood. In the context of increasing global environmental degradation, the notion of "green" has become synonymous with concepts such as pollution reduction, environmental protection, and sustainable development (Huiling & Dan, 2020).

Value chains refer to the sequence of events within an organisation that produce a market-valued product. Organisations are systems consisting of inputs, transformation processes, and outputs. Resources must be acquired and consumed for every system action. Organisational value chain activities determine costs and income (Simatupang et al., 2017). Improved control over the value chain can be achieved by reducing costs throughout production, R&D, design, raw material acquisition, and processing (Ruan, 2020). Value chain analysis serves as an invaluable management tool, facilitating the identification of essential activities that contribute to developing a superior product or service, ultimately delivering significant value to the customer.

Building sustainable solutions to overcome ambiguity requires value chain flexibility (Dwivedi et al., 2021). To obtain a comprehensive understanding of the cost drivers and sources of differentiation, value chain analysis divides an organisation's activities and operations into strategically relevant components. This approach allows the business to make necessary adjustments (Razak & Vattikoti, 2018). There are two ways that links can result in a competitive advantage: coordination and optimisation. To accomplish this, a company needs to maximise these connections in accordance with its strategy (Shapiro et al., 1993). Eco-design in supply chain initiatives greatly increases economic, environmental, cost-cutting, and intangible effects. Only cost savings were greatly enhanced by reverse logistics.

In this study, the researcher used the green value chain model, with her own operational process and definition, in which the green value chain starts from Green Design, Green Raw Materials, Green Products, Green Suppliers, Green Pricing, Green Distribution, and Green Customers, leading to Green Business and achieving Business Sustainability. In every chain, it carries the green value component, making the business not only profitable and successful but also sustainable. Business sustainability is challenging to maintain, so this Green Value Chain Model will be adopted by every business organisation to ensure sustainability. Sustainability, globalisation, cooperation, intangible assets, adaptability, and agility are the factors driving the shift from value chain to value network. (Ricciotti, 2020). Competitive advantage is determined by unique items and advantageous prices (Nu'man et al., 2020).

Through qualitative research methods, including face-to-face interviews, site visits to Cobonpue's production facilities, and an examination of Kenneth Cobonpue's practices, this study will show how businesses in the creative sector can enhance their environmental responsibility while maintaining high standards of design and innovation.

The objectives of the study are: to identify sustainable practices; to consider environmental impacts; to evaluate economic benefits of sustainability; to identify challenges and opportunities; and to develop a Green Value Chain Model.

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2. Research Methodology

This study employs a qualitative case study approach to gain an in-depth understanding of the green value chain best practices of Kenneth Cobonpue. The case study method is chosen to provide a detailed, context-specific analysis of Kenneth Cobonpue's sustainable practices within his business environment.

For data collection**,** face-to-face interviews were used. A semi-structured interview guide was prepared to raise questions for Kenneth Cobonpue, and Ms Estela Ocampo, the Executive Consultant and the former Chief Operating Officer of the company. His design, production and marketing staff. These interviews aim to gather insights into the sustainable practices implemented and their perceived impact. Observational visits to Cobonpue's production facilities and workshops are conducted to observe green practices in action directly. This includes examining the materials used, production processes, and waste management practices. Relevant documents, including company reports, sustainability reports, marketing materials, journal articles, and websites, were reviewed to supplement the collected data.

Thematic, document analyses and data triangulation were used. Via thematic analysis, the obtained data is evaluated for recurring themes. Document analysis encompassed company reports, sustainability reports, marketing materials, journal papers, and websites, which were reviewed to complement data collection and to identify eco-value chain themes and motifs. Code the data and organise it into topics that align with K. Cobonpue's sustainable practices. Data triangulation ensured validity and reliability by cross-checking information from multiple sources (interviews, site visits, articles, and websites). All participants were informed of the study's purpose and provided consent before the interview.

The study was limited to the practices of Kenneth Cobonpue and may not be generalisable to other designers or industries. As a qualitative study, the findings were subject to the researcher's interpretations, which may introduce bias.

3. Results and Discussion

The researcher conducted a face-to-face interview with Kenneth Cobonpue and Ms Estela Ocampo, the Executive Assistant and the Former Chief Operating Officer of the company. Also, the company's design, production, and marketing staff. Below are their responses to the key questions, aligned with the study's objectives.

3.1. Sustainable Green Value Chain Practices

To identify and document the specific green-value-chain practices implemented by Kenneth Cobonpue in his design and manufacturing processes, the following questions were posed.

Question: Can you walk us through the specific sustainable practices you've integrated into your design and manufacturing processes?
Response: "Our competitive advantage lies in the creative and intricate handwoven designs of our furniture products. Designs that reflect a level of artistry, skill, and patience, distinctive of Filipino craftsmanship and challenging to replicate elsewhere. Moreover, we primarily utilise organic and indigenous raw materials, such as rattan, bamboo, abaca, wood, steel, polyethene, microfiber, and nylon, all of which are abundantly available in the Philippines. This reliable access to local materials enables us to maintain consistent production and offer competitive pricing in the global market."

Indigenous materials and techniques are frequently used in these woven designs, making it challenging for artisans unfamiliar with the cultural background or for mechanical production to imitate them. The intricate weaving designs, which are often done by hand, require not only physical stamina but also a thorough understanding of material behaviour and design principles. As a result, furniture is produced that is not only aesthetically pleasing but also environmentally friendly and structurally robust.

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Question: What inspired you to adopt these green practices, and how have they evolved?
Response: "We take great pride in how our innovative products have captured attention both locally and internationally. Our designs have attracted distinguished clients, including internationally acclaimed actress Angelina Jolie and Facebook founder Mark Zuckerberg. Our pieces are also featured in prestigious luxury hotels around the world. In addition, we have received numerous local and international awards that recognise our commitment to design excellence and craftsmanship."

The outstanding quality, cultural diversity, and visual appeal intrinsic to Filipino workmanship are highlighted by the widespread recognition and market penetration of creative furniture products. Kenneth Cobonpue's designs, which skillfully combine traditional weaving methods with modern utility, have attracted interest both domestically and internationally. High-profile customers like Facebook founder Mark Zuckerberg and internationally famous actress Angelina Jolie have shown their support for their items, which is proof of their handmade quality and worldwide appeal.

Question: How do traditional Filipino materials and craftsmanship play a role in your sustainability efforts?
Response: "By focusing on the use of natural indigenous materials, and recycling the by-products to other products, we minimise the waste, thus the creation of the Kurated Company sustains the Philippine tradition using artisan craftmanship, which is very intricate, using their hands that machines could not make".

The conversion of production waste into new product lines is a significant breakthrough that reduces environmental impact and increases resource efficiency. This approach demonstrates a dedication to sustainability that goes beyond simple compliance and into the field of creative regeneration, where trash is turned from a liability into a source of value.

3.2. Environmental Impact

Question: How do your material choices and production methods help reduce environmental impact?
Response: "We make use of indigenous materials that are abundantly available in the country, ensuring sustainable sourcing. In addition, we practice a zero-waste approach by recycling every bit of excess material. Our recycled creations can be found through our KCurated brand."

K-Curated's zero-waste strategy, which turns every piece of industrial waste into new product lines, is a distinctive characteristic of its business model. By turning potential trash into valuable commodities, this method is a prime example of sustainable innovation and circular design. In addition to reducing their environmental impacts, these recycling programs encourage innovation and variety in product design.

Question: What steps do you take to minimise waste and improve energy efficiency in your operations?
Response: "We recycle our production waste and by-products into new creations, which are showcased through KCurated. Founded by Kenneth Cobonpue, KCurated is a local home décor company established to offer a unique line of gifts and accessories as an alternative to the main Kenneth Cobonpue brand. The brand was created to promote accessible yet exclusive luxury for the Filipino market. Positioned as an aspirational entry point, KCurated serves as a strategic introduction to the Kenneth Cobonpue brand."

K-Curated's zero-waste strategy, which turns every piece of industrial waste into new product lines, is a distinctive characteristic of its business model. By turning potential trash into valuable commodities, this method is a prime example of sustainable innovation and circular design. In addition to reducing their environmental impacts, these recycling programs encourage innovation and variety in product design.

3.3. Economic Benefits

Question: What economic benefits have you observed from implementing sustainable practices in your business?
Response: "We have experienced an increase in sales from people who value sustainable production methods. They also promote our work among their circle, expanding our reach. "

The deliberate incorporation of indigenous materials, sustainable production methods, and culturally grounded design has facilitated substantial development in sales, profitability, and long-term revenue generation for the organisation. By synchronising its operations with global trends in ethical purchasing and environmentally responsible design, the firm has effectively attracted a diverse clientele from both local and international

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markets. The company's strategy cultivates a sustainable economic ecosystem that integrates traditional craftsmanship, ecological responsibility, and market innovation to yield both financial benefits and socio-cultural impact.

Question: How have these practices influenced your brand's competitiveness in both local and international markets?
Response: "These practices have helped us to develop a distinctive look, and have increased brand identity and recall."

Participation in trade fairs provides exceptional chances for direct interaction with prospective buyers, industry players, and partners. Local trade fairs enhance neighbourhood connections and bolster domestic market presence, whereas international exhibitions provide insight into global trends, consumer preferences, and innovative technology. These venues serve as forums for benchmarking and strategic networking, essential for improving operations and enhancing product visibility.

Question: In what ways do your sustainability efforts support local artisans and the broader Philippine economy?
Response: "The direction to merge modern, artistic and traditional techniques has kept our local crafts alive. We have trained younger people in weaving, meticulous upholstery work, and even painting. Our designs continue to evolve. With the introduction of more artistic lines, we are employing young people with potential to do artistic work in painting and form making."

Focusing on affluent consumers elevates brand reputation and enables the company to set higher price points, thereby augmenting profit margins and financial viability. This strategic orientation facilitates investment in human capital, particularly in retaining and augmenting skilled artisan labour. The company fosters the preservation of traditional knowledge systems and the socio-economic advancement of artisan communities by offering permanent employment and equitable remuneration to local artisans.

3.3. Challenges and Opportunities

Question: What are some of the biggest challenges you've faced in integrating sustainable practices into your value chain?
Response: "One of our biggest challenges is an ageing skilled workforce. Many of our skilled weavers are retiring or will be retiring in a couple of years. Fewer young people want to do weaving. They prefer to find jobs in the malls or work in business process outsourcing companies. These types of work are not as tedious as weaving, painting, and other manual labour."

The diminishing number of experienced artisans in the Philippines poses a significant obstacle to the viability of traditional handicraft businesses, especially those dependent on complex manual processes such as weaving and painting. With numerous experienced artisans retiring, there is an imperative to nurture a new generation of artisans who embody the requisite technical abilities, patience, passion, and cultural appreciation essential for this labour-intensive vocation.

Question: What opportunities have emerged as a result of your commitment to sustainability in the Philippine design industry and in the global market?
Response: "We have become a go-to business for others who want unique work that uses natural materials. There is a desire to acquire beautiful objects that are meticulously made by human hands."

Given the growing customer awareness and preference for ecologically sustainable products, one can expect increased sales and profitability. Current market trends reveal an increasing number of individuals actively pursuing 'green' products, defined as non-toxic, ethically produced, and environmentally sustainable. This change in consumer behaviour indicates a broader social commitment to health, environmental responsibility, and sustainable development, thereby positioning eco-conscious enterprises for enhanced commercial success.

Question: Are there specific products or collections that have performed better due to their eco-friendly appeal?
Response: "The Lolah Collection is very distinctive as it largely uses rattan material to create its unique form. This collection includes chairs, sofas, nd tables made from rattan strips woven into fluid, organic shapes. The Lolah Collection exemplifies Cobonpu's mastery of rattan and his innovative approach to furniture design".

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Kenneth Cobonpue's Lolah Collection displays a revolutionary vision in furniture design, reinterpreting indigenous materials via contemporary design principles. His work surpasses traditional uses of r ttan by altering its structural and aesthetic characteristics to produce sculptural sculptures that are both utilitarian and expressive. The collection's success is attributed to its aesthetic allure, sustainable workmanship, cultural continuity, and design innovation.

Question: How do you measure the financial return on investment (ROI) of your sustainable initiatives?
Response: "We measure ROI of sustainable initiatives not only in terms of quantity of products sold, but also in terms of goodwill and positive perception of the brand. This translates into higher interest in our product range and customer loyalty. Education is also part of our advocacy. We have increased the number of our On-the-Job Trainees (OJT) in many business units to provide tangible industry experience and potential job opportunities to successful candidates".

The continuous increase in profit margins and the growing client base, both domestically and globally, are essential measures of the enterprise's strategic success and market significance. These financial benefits indicate height ned consumer demand as well as the company's ability to innovate, adapt, and produce culturally relevant, high-quality products. As the enterprise grows, it strengthens its commitment to corporate social responsibility by enhancing its On-the-Job Training (OJT) programs, thereby supporting workforce development and the transfer of artisanal skills to future generations.

Question: Have your green practices opened up new markets or business opportunities, locally or internationally?
Response: "Yes, currently we have launched a creative hub that merges culinary art, design, and visual expression in Manila at FABLE Café + Lounge, Showroom, and Cloud Grey Gallery—all under one roof at the Grand Hyatt Manila Residences Tower in Bonifacio Global City (BGC). Currently, we have offices and showrooms in Cebu, Manila, Germany, Portugal, and New York. There is an increase in orders for custom installations that are artistic and unique".

The creation of a multifunctional creative hub, including FABLE Café + Lounge, a design showroom, and the Cloud Grey Gallery within the Grand Hyatt Manila Residences Tower in Bonifacio Global City (BGC), signifies a purposeful integration of culinary arts, design innovation, and visual expression. This integrated space functions as both a business venue and a cultural platform that promotes experiential engagement with Filipino innovation and craftsmanship.

The company's global expansion, featuring offices and showrooms in Cebu, Manila, Germany, Portugal, and New York, exemplifies its ability to scale operations while preserving cultural integrity. These international outposts serve as essential hubs for market entry, cultural exchange, and the global advancement of Filipino artisanal excellence. The brand's presence in many geographic regions highlights its adaptability and dedication to integrating Philippine design into the global creative economy.

4. Findings of the Study

4.1. Environmental Impact

Reduced Environmental Footprint. By using natural and renewable materials, Kenneth Cobonpue significantly reduces the environmental impact of his products. This helps conserve resources and minimise pollution. The conditions and customs of the local population influence design within a particular culture (Fedelizo, 2023).

Waste Minimization. Implementing waste-reduction strategies, such as recycling and upcycling, reduces the amount of waste sent to landfills, contributing to a cleaner environment. Waste materials are converted into other materials. Kenneth Cobonpue founded the local home écor brand, KCurated (KC). The purpose of the brand's creation was to provide a home décor and accessory-focused alternative to the leading KC brand, positioning it as an exclusive, reasonably priced luxury brand for the Filipino market (Fedalizo, 2023).

Energy Efficiency. Adopting energy-efficient production processes lowers greenhouse gas emissions, helping to combat climate change. Kenneth Cobonpue's use of natural materials and eco-friendly processes inspires new design possibilities and encourages others to think outside the box. The conditions and customs of the local population influence design in a particular culture (Rivera-Lutap, 2023). It prioritises the use of natural and

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renewable materials, such as rattan, bamboo, and abaca, which are abundant in the Philippines, and also supports local agriculture.

4.2. Economic Benefits

Cost Savings. Sustainable measures can save money over time. Example: Energy-efficient processes and risk minimisation reduce operational costs.
Market Competitiveness. Green practices can give firms a competitive edge as consumers become increasingly environmentally conscious. Kenneth Cobonpue's commitment to sustainability can increase brand loyalty and attract eco-conscious customers.
Support for Local Economy. By promoting local craftsmanship and sourcing materials locally, Cobonpue supports the local economy and creates job opportunities within the community.

4.3. Social Implications

Community Engagement. Kenneth Cobonpue's practices foster a sense of community by involving local artisans and craftsmen in the production process. This not only preserves traditional skills but also empowers local communities.
Consumer Awareness. By highlighting the importance of sustainability in design, Kenneth Cobonpue raises consumers' awareness of the environmental impact of their purchasing decisions. This can lead to more informed and responsible consumer behaviour.

4.4. Industry Implications

Setting a Benchmark. Kenneth Cobonpue's green practices set a benchmark for other designers and manufacturers in the industry. His success demonstrates that sustainability can be integrated into high-quality design and production.
Innovation and Creativity. Embracing sustainability can drive innovation and creativity, specifically, in the creative industry. The foundation of creative cities that support society's overall well-being is the creative industry (Rivera-Lutap, 2023). Kenneth Cobonpue's use of natural materials and eco-friendly processes inspires new design possibilities and encourages others to think outside the box.

4.5. Sustainable Material Sourcing

Kenneth Cobonpue prioritises the use of natural and renewable materials, such as rattan, bamboo, and abaca, which are abundant in the Philippines. This will not only reduce environmental impact but also support local agriculture. Bamboo fibres, prevalent in the Philippines, are a popular reinforcement for polymeric moulds due to their good physico-mechanical properties (Behera et al., 2025). These materials reflect Kenneth Cobonpue's commitment to sustainability and his ability to blend traditional craftsmanship with modern design techniques. His innovative use of natural materials not only enhances the aesthetic appeal of his creations but also supports environmental responsibility.

Waste Minimisation. The study found that Kenneth Cobonpue's production processes are designed to minimise waste. Techniques such as recycling offcuts and repurposing waste materials into new products are commonly practised.

Energy Efficiency. Kenneth Cobonpue's facilities incorporate energy-efficient technologies, including LED lighting and energy-saving machinery.

Local Craftsmanship. A significant finding is Kenneth Cobonpu's commitment to promoting local craftsmanship. Employing local artisans and preserving traditional skills will not only enhance product quality but also contribute to the local economy and cultural heritage.

Environmental Impact. The study highlights a notable reduction in the environmental footprint of Cobonpue's operations. This includes lower carbon emissions, reduced waste, and sustainable use of resources.

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Economic Benefits. Adopting green business practices will lead to long-term cost savings. Energy efficiency and waste reduction will minimise operational costs, while the use of local materials has reduced transportation expenses.

Market Competitiveness. Cobonpue's commitment to sustainability has enhanced his brand reputation and market competitiveness. Eco-conscious consumers are drawn to his products, boosting sales and customer loyalty.

4.6. Challenges and Opportunities

Challenges. The study identifies difficulties such as higher initial costs of sustainable materials and technologies, and the need for continuous innovation to maintain sustainability standards. The opportunities include expanding the market for sustainable products, leveraging technological advancements for further efficiency, and setting industry benchmarks for sustainability.

Opportunities. Kenneth Cobonpue has received numerous prestigious awards throughout his career, recognising his innovative designs and contributions to the field of industrial design, which could be an excellent opportunity to attract both local and international markets. Below are some of the notable awards he has received, which could lead to bigger and more sustainable business opportunities.

Maison et Objet's Asian Designer of the Year (2014). Cobonpue was named the first Maison et Objet Designer of the Year for Asia, in recognition of his impact on the field of furniture and design. (Wikipedia contributors, n.d.).
Gawad CC Para sa Sining Award for Design (2020). This is the highest distinction given by the Cultural Centre of the Philippines (CCP) to Filipino artists for their contributions to Philippine arts and culture. Cobonpue was the first recipient in the field of design. (Wikipedia contributors, n.d.).
Pratt Le ends Award (2023). Awarded by the Pratt Institute in New York, this honour recognises significant contributions to the global furniture and design industry. Cobonpue is the first Asian to receive this Award (https://kennethcobonpue.com/stories/kenneth-cobonpue-now-a-pratt-legend).
Good Design Award: ASEAN Design Collection. Cobonpue has won five Japan Good Design awards, which recognise excellence in design and innovation (Kenneth Cobonpue, n.d.).
Singapore International Design Competition (Grand Prize) (2004). He received the grand prize at this competition, highlighting his exceptional design skills. (Kenneth Cobonpue, n.d.).
Design for Asia Award, Hong Kong. (2005) This Award celebrates design excellence in Asia, and Cobonpue's work has been recognised for its creativity and impact (Kenneth Cobonpue, n.d.).
American Society of Interior Designers (ASID) Top Pick (2012). Cobonpue's designs have been selected as top picks by the ASID, showcasing his influence in the interior design community (Kenneth Cobonpue, n.d.).
Prix D'Excellence Coup de Coeur Award: SIDIM Montreal (2011). This Award further acknowledges Cobonpue's innovative approach to design and his ability to captivate international audiences (Kenneth Cobonpue, n.d.).

These awards reflect Kenneth Cobonpue's dedication to pushing the boundaries of design and his commitment to sustainability and craftsmanship. His work continues to inspire and set standards in the global design industry. The numerous awards Kenneth Cobonpue has received have had a significant impact on his career in several ways, such as increased recognition and credibility, global recognition, expanded market reach, increased demand and sales, inspiration and influence, and opportunities for collaboration.

Overall, the awards Kenneth Cobonpue has received have significantly boosted his career, enhancing his reputation, expanding his market reach, and inspiring both consumers and fellow designers. His achievements underscore the importance of creativity, sustainability, and craftsmanship in the design and creative industry. Kenneth Cobonpue's design philosophy is deeply rooted in nature and sustainability, blending traditional craftsmanship with modern aesthetics.

Here are some key aspects of his philosophy.
Nature as the Soul. Kenneth Cobonpue believes that nature is always the soul of his projects. His designs often draw inspiration from natural forms and structures, such as plants, animals, and landscapes (1stDibs, n.d.).

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Organic Lines. His creations feature organic lines and shapes that mimic nature's fluidity and elegance. This approach results in designs that are both visually appealing and harmonious with their surroundings. (1stDibs, n.d.).
Use of Natural Materials. Cobonpue has been using natural materials long before sustainability became a mainstream concern. Materials like rattan, bamboo, and abaca are integral to his designs, reflecting his commitment to environmental responsibility (1stDibs, n.d.).

Eco-Friendly Practices. His brand adopts eco-friendly practices at every stage of production, from material procurement to disposal. This ensures that his pieces have minimal environmental impact (1stDibs, n.d.).

Preserving Heritage. Cobonpue values traditional craftsmanship and works closely with local artisans. This not only preserves cultural heritage but also ensures the production of high-quality, handcrafted products (1stDibs, n.d.).

Innovation in Craft. While honouring traditional techniques, Cobonpue continually innovates, blending old and new methods to create unique, contemporary designs (1stDibs, n.d.).

Functional Aesthetics. Cobonpue's designs are not just visually striking but also highly functional. He aims to create pieces that offer both beauty and practicality, making everyday objects into works of art (1stDibs, n.d.).

Comfort and Luxury. His furniture often combines comfort with luxury, ensuring that each piece is not only aesthetically pleasing but also comfortable and inviting (1stDibs, n.d.).

Cultural Fusion. Cobonpue's work reflects a fusion of different cultures, drawing inspiration from various parts of the world. This global perspective adds a unique dimension to his designs.

Collaborations. He collaborates with international designers and brands, bringing diverse influences into his work and expanding his creative horizons (Porter, n.d.).

Progressive Design. Cobonpue believes that design is a living process that must evolve in response to the changing world. He avoids being boxed into a specific aesthetic, allowing his style to grow and adapt over time (Porter, n.d.).

Innovation and Creativity. His philosophy emphasises the importance of innovation and creativity, encouraging constant exploration and experimentation (Porter, n.d.).

Kenneth Cobonpue's design philosophy is a testament to his ability to blend nature, sustainability, and craftsmanship into timeless and innovative creations that resonate with people around the world. He has created numerous iconic designs that have garnered international acclaim. Some of his most notable pieces are the Yoda Chair, Bloom Chair, Dragnet Lounge Chair, Voyage Bed, Lolah Collection, Chiquitita Stool, Little People Lamp, La Luna Hanging Lamp, Croissant Sofa and Bouquet Table (Humaling, n.d.). These designs reflect Kenneth Cobonpue's unique ability to merge traditional craftsmanship with contemporary design, resulting in pieces that are both functional and visually captivating. His work continues to inspire and set trends in the world of furniture and interior design.

4.7. Green Value Chain Model

The proposed Green Value Chain Model (see Figure 1 below), based on the findings of the study, would serve as a model or guide for budding entrepreneurs, businessmen, investors, and Micro, Small and Medium Enterprises (MSMEs) who wanted to excel in the global market to make their business not only profitable and successful but also sustainable. Sustaining the business is crucial in a very competitive international market.

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Figure 1. Proposed Green Value Chain Model
Source: the author

Green Design and Green Raw Materials. Designing products with environmental impact in mind, minimising waste, maximising efficiency, and using eco-friendly concepts. Leads to the selection of Green Raw Materials that support the design's sustainability goals. Eco-conscious product design minimises waste, boosts efficiency, and embraces sustainable principles, driving the use of green raw materials aligned with environmental goals (Delaney et al., 2022; Ferro et al., 2021; Popescu et al., 2024). This approach supports circular economy practices and promotes long-term sustainability across industries (Majid et al., 2023; Maqsood & Altaf, 2023).

Green Raw Materials and Green Products. Sourcing renewable, recyclable, or biodegradable materials reduces environmental harm and supports sustainable design. These materials inform the selection of green suppliers who can provide them responsibly, reinforcing eco-conscious supply chain practices (Raghunathan et al., 2025; Berry et al., 2025; Rastogi et al., 2025). Goods that are energy-efficient, non-toxic, recyclable, or made from sustainable resources. Green products are designed to minimise environmental impact throughout their life cycle. These goods are typically energy-efficient, non-toxic, recyclable, or made from renewable and sustainable resources. Their development reflects a commitment to reducing greenhouse gas emissions, conserving natural resources, and promoting human health and safety (Popescu et al., 2024; Ferro et al., 2021). Designing green products also involves considering their entire life cycle—from raw material sourcing and manufacturing to usage and end-of-life disposal. This holistic approach ensures that environmental benefits are maximised and that the products meet evolving sustainability standards across industries (Liddell et al., 2023).

Green Suppliers. Partnering with vendors that adhere to sustainable practices across sourcing, production, and logistics is a critical strategy for advancing environmental responsibility in product development. These partnerships ensure that materials and processes used throughout the supply chain align with ecological standards, reduce carbon footprints, and promote ethical resource management. By collaborating with such vendors, organisations can create green products that not only meet but often exceed environmental compliance benchmarks, contributing to long-term sustainability goals and consumer trust in eco-conscious brands (Runtuk et al., 2024; Tavanti, 2025; Khizar et al., 2024).

Green Pricing. Setting prices that consider environmental costs, fair trade, and long-term value for customers and the planet. Green pricing is a strategic approach to setting product prices that internalises environmental costs, promotes fair trade, and reflects long-term value for both consumers and the planet. Unlike traditional pricing models that focus solely on production and market dynamics, green pricing incorporates the ecological footprint of goods and services, including carbon emissions, resource depletion, and pollution (Ingenbleek, 2024; Zou et al., 2024). Ultimately, green pricing serves as a tool for aligning profitability with environmental stewardship, helping organisations transition toward more sustainable business models while meeting regulatory and stakeholder expectations (Le Moigne & Lepot, 2024).

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Green Distribution and Green Customers. Using low-emission transport, minimal packaging, and efficient delivery systems to reduce carbon footprint. Implementing low-emission transportation, minimal packaging, and efficient delivery systems is essential for reducing the carbon footprint of logistics operations. Low-emission transport options, such as electric vehicles, hydrogen-powered trucks, and multimodal systems, significantly cut greenhouse gas emissions from freight and last-mile delivery (Bukhari et al., 2022; Jahagirdar et al., 2025). Minimal packaging strategies—such as using recyclable, biodegradable, or reusable materials—further reduce waste and energy use in the supply chain. Efficient delivery systems, supported by data analytics and smart logistics hubs, streamline operations and reduce unnecessary trips, contributing to lower emissions and improved sustainability metrics (Solaymani & Botero, 2025)—consumers who actively seek and support environmentally responsible products and companies. Green consumers are individuals who actively seek out and support products, services, and companies that demonstrate environmental responsibility. Their purchasing decisions are influenced by ecological awareness, ethical values, and a desire to reduce personal and societal environmental impact. These consumers prioritise energy-efficient, recyclable, biodegradable, and sustainably sourced goods, often aligning their choices with broader goals of climate action and resource conservation (Kumar, 2021; Alghamdi & Agag, 2024). Their support strengthens the foundation of a Green Business.

Green Business. An enterprise that integrates sustainability into every aspect, from design to customer engagement. This holistic approach ensures long-term business sustainability. By aligning business practices with sustainability principles, green businesses foster resilience, innovation, and long-term value creation (Lozano, 2018; Schmidpeter, 2025).

Business Sustainability. Business sustainability refers to the strategic pursuit of economic success while actively preserving natural resources, supporting communities, and ensuring long-term viability. It involves integrating environmental stewardship, social responsibility, and economic resilience into core business operations. Sustainable businesses adopt practices such as resource-efficient production, ethical labour standards, and community engagement to align profitability with planetary and societal well-being (McAllister, 2025; Chandore & Tigharkar, 2025).

This holistic approach not only mitigates environmental risks but also enhances brand reputation, stakeholder trust, and operational efficiency. By embracing sustainability, businesses can adapt to global challenges such as climate change, resource scarcity, and social inequality, positioning themselves for long-term success in a rapidly evolving marketplace (Makaya & Cateura, 2025). Research consistently shows that sustainable practices contribute to financial performance, innovation, and competitive advantage, making sustainability a strategic imperative rather than a peripheral concern (Roffé & González, 2024).

Conclusions

This study reveals that Kenneth Cobonpue's green value chain best practices deliver not only environmental sustainability but also economic gains, social impact, industry transformation, and sustainable material sourcing. The novelty lies in the Green Value Chai Model, a holistic framework comprising *green design*, which embeds an eco-conscious principles at the conception stage; *green raw materials*, prioritising renewable and responsibly sourced inputs; *green suppliers*, building partnerships aligned with sustainability standards; *green products*, creating innovative, durable, and environmentally friendly outputs; *green pricing*, integrating fair and sustainable pricing strategies; *green distribution*, minimising carbon footprint across logistics and delivery, and *green business*, fostering a culture of *business sustainability* for long-term viability. By adopting this model, companies can transform sustainability into a profitable and resilient strategy, driving innovation, operational efficiency, and market success. Cobonpue exemplifies how design-led enterprises can lead this paradigm shift, proving that green practices are both ethical and economically rewarding.

Based on the insights gathered from this study, the researcher highly recommends the following:
1) to implement the proposed Green Value Chain within the furniture and creative industries, to Budding entrepreneurs, Exporters, Micro, Small and Medium Enterprises (MSMEs) as a strategic business model that holistically addresses the four pillars of sustainability**,** the Product, People, Profit, and Planet (4PS). This model promotes responsible sourcing, ethical labour practices, circular design, and environmental stewardship, thereby

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enabling businesses to achieve long-term viability, competitive advantage, and meaningful contributions to sustainable development;

2) strengthen Support for Artisan Communities. Government agencies, private institutions, and design schools should collaborate to provide sustained support for local artisans through training, funding, and market access. The success stories shared by Mr Kennet Cobonpue and Ms Estela Ocampo highlight the transformative power of mentorship and opportunity in elevating craftsmanship to global standards;

3) promote Philippine Design Globally. There is a need to amplify the global visibility of Filipino design through international exhibitions, trade fairs, and cultural diplomacy. The narratives in this study affirm that Filipino creativity is world-class and deserves a prominent place on the global stage;

4) institutionalize Support for Creative Enterprises. Develop and implement policies that provide financial incentives, tax breaks, and grants for creative startups and artisan cooperatives. This will encourage innovation and sustainability in the sector;

5) integrate Creative Industry Studies into Entrepreneurship Curricula. Offer interdisciplinary programs that combine design, entrepreneurship, and cultural studies to prepare students for careers in the creative economy.

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USE OF ARTIFICIAL INTELLIGENCE FOR BUSINESS DECISION-MAKING*

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Abstract. The Decision Model and Notation (DMN) standard provides a unified framework for the representation of business decisions, with decision tables constituting its central construct. Despite the advantages offered by the manual creation of DMN decision tables from textual descriptions in terms of transparency and analysis, the process is time-consuming and prone to errors. This results in a discrepancy between the textual rules and the formal structures required for automation. The proposed framework integrates Large Language Models (LLMs) with Retrieval-Augmented Generation (RAG), facilitating the automated conversion of natural language descriptions into decision tables. The framework utilises a modular pipeline comprising schema injection, retrieval of relevant domain-specific data, prompt composition, generation, and validation. This design guarantees that the resulting decision tables comply with DMN's rigorous XML-based specification while also capturing the contextual meaning of the original rules. A significant challenge in relying exclusively on LLMs is their proclivity to hallucinate or deviate from the required format. The integration of RAG has been demonstrated to mitigate these issues by grounding generation in reliable sources, enhancing both factual accuracy and structural consistency. The experimental results demonstrate that the LLM-RAG configuration significantly enhances the precision and robustness of generated DMN decision models, producing valid and contextually appropriate outputs with minimal human intervention. The advancement of automation in the field of decision modelling has the potential to enhance the efficiency, transparency and adaptability of decision-making processes. The findings indicate a pathway towards scalable, explainable, and verifiable decision automation across diverse business domains.

Keywords: ICT for business; Decision Model and Notation (DMN); Decision-making; Large Language Model; Natural Language Processing; Retrieval-Augmented Generation (RAG); Artificial Intelligence (AI)

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JEL Classifications: C02, C4, D81, M19

Additional disciplines: information and communication; informatics

1. Introduction

In today's data-driven economy, organisations increasingly rely on formalised decision models to ensure consistent, transparent, and adaptable operations (Mugunzva & Manchidi, 2024; Gavaza, 2025; Španková & Sochuľáková, 2025). The Decision Model and Notation (DMN) standard, developed by the Object Management Group (OMG), has emerged as a leading framework for modelling complex decision logic using structured

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decision tables (Calvanese, Dumas, & Maggi, 2018). These tables allow business users and analysts to formalise rule-based decisions in a format that is both machine-readable and human-interpretable. However, despite the growing adoption of DMN, the process of manually creating decision tables from natural language rules remains labour-intensive, error-prone, and inaccessible to non-experts.

A decision table is one way to represent the decision logic associated with a Decision Requirements Diagram artefact. The table includes all necessary inputs for determining the outputs for every possible combination of inputs. Decision tables, along with hierarchical structures of decision tables, are a well-established method for representing decision logic (Arco et al., 2021; Vandevelde, Aerts & Vennekens, 2023; van Woensel & Motie, 2024).

The rapid advancement of Large Language Models (LLMs), such as GPT-4 and Claude 3.5, has opened new possibilities for automating decision model generation. These models are capable of interpreting natural language instructions, identifying decision variables, and producing structured outputs. Recent research has demonstrated that LLMs can generate basic DMN tables from unstructured text, but challenges persist in ensuring rule completeness, exclusivity, and logical consistency. Furthermore, standalone LLMs often suffer from hallucinations, especially when critical domain-specific knowledge is missing. To address these limitations, the integration of Retrieval-Augmented Generation (RAG) has been proposed. RAG improves generation accuracy by allowing the model to query external knowledge bases during inference, thereby grounding outputs in relevant, up-to-date information. Combined with schema-aware prompting and post-generation validation tools, this approach significantly enhances the reliability of LLM-generated DMN tables.

This research investigates how LLMs and RAG can be jointly leveraged to automate the generation of DMN decision tables from natural language. We analyse the structure of DMN models, identify key bottlenecks in their manual creation, and propose a framework that enables automated generation, validation, and deployment of decision logic. Through empirical testing and literature-driven analysis, we aim to reduce the complexity of DMN modelling and move toward scalable, LLM-driven decision automation.

The primary aim of this research is to develop and evaluate a modular framework for the automated transformation of natural language business rules into DMN decision tables by leveraging LLMs enhanced with RAG. The study seeks to address the challenges of schema compliance, logical consistency, and factual grounding in the automatic generation of decision logic.

To achieve this aim, the study pursues the following objectives: (1) to analyse existing approaches to DMN-based decision modelling and identify the key limitations of manual table construction; (2) to explore the capabilities and constraints of LLMs in generating structured DMN models from textual descriptions; (3) to design a hybrid architecture integrating schema injection, retrieval, prompt composition, generation, and validation components; (4) to conduct empirical testing comparing the performance of LLM-only and LLM+RAG configurations in a realistic decision-making scenario; and (5) to evaluate the impact of RAG on the accuracy, completeness, and reliability of automatically generated DMN tables. Accordingly, this research is guided by the following questions:
(1) To what extent does the integration of RAG improve the accuracy and completeness of DMN decision tables generated by LLMs?
(2) How do schema injection and retrieval mechanisms contribute to reducing structural and logical inconsistencies in automated model generation?
(3) What is the potential of the proposed framework to enable scalable, explainable, and verifiable decision automation across business domains?

2. Literature Review

The DMN model is specifically designed for business professionals with the decision table as its core construct. Key elements within DMN tables are built upon FEEL, the standard DMN language, which is based on a simple data model and uses three-valued logic (true, false, null). We can highlight several key elements. An Information Item Name identifies what the table represents, typically linked to the decision logic. The table includes input

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clauses made up of simple input expressions, such as names or conditions, and may define allowed values. These inputs serve as the basis for the rules within the table. Outputs are defined through the output clauses, each containing a name and specifying allowed output values. The decision table's rules collectively establish how particular combinations of input values lead to specific outputs, forming a clear, structured approach to decision-making. The rules can be presented in rows or columns, depending on the table's orientation. Thera are normally several rules, which do not overlap. The hit policy indicator is required to recognise the table type and understand the decision logic.

Empirical applications, particularly in complex domains such as healthcare, underscore the practical utility of DMN in automating decision-intensive processes. By enabling decisions to be modelled and evaluated independently, DMN improves decision quality, supports transparency, and enhances organisational adaptability to frequent changes in business rules. Thus, DMN decision tables are an essential tool for advancing automated decision-making processes in diverse operational contexts (Corea et al., 2024).

The goal of DMN is to provide the necessary constructs for decision modelling, allowing to be automated. With the growing adoption of DMN decision tables, there is an increasing need for a comprehensive analysis of these tables. Findings indicate that model complexity decreases when processes are distilled to their essence, avoiding hard-coded decision logic (Funk, 2023). The introduction of the DMN standard has sparked a variety of technical and empirical studies focused on decision models created using DMN (Fernandez et al., 2023).

The integration of DMN with BPMN represents a paradigm shift in how organisations manage and automate their workflows. In practice, BPMN activities that require decision-making, such as "business rule tasks," can reference DMN decision models. These references link the inputs and outputs of a BPMN process to the decision-making logic encoded in DMN tables. For instance, in a procurement process, a BPMN task to approve purchase orders can utilise a DMN decision table to evaluate the order's compliance with business policies and budget constraints. This linkage ensures that processes remain consistent, and decisions are executed uniformly, regardless of the process context (Etikala, 2021). . By providing a standardised framework for integrating processes and decisions, the BPMN-DMN synergy enables organisations to streamline their operations and adapt more effectively to a dynamic business landscape (Kanyuka & Mahfoud, 2024).

The automation of DMN table generation using LLMs represents a significant advancement in decision automation. Traditional DMN modelling relies on manual rule definition, requiring domain expertise and time investment. The integration of LLMs into this process offers the potential to streamline DMN table generation by transforming natural language descriptions into structured decision logic (Boonmepipit & Suwannasart, 2019). While LLMs have demonstrated strong capabilities in structured data generation, several key challenges remain when applying them to DMN modelling.

Ensuring schema compliance is one of the primary challenges in LLM-driven DMN table generation. Since DMN tables are implemented in an XML-based format, every generated table must adhere to predefined input clauses, output clauses, hit policies, and decision rules to be executable in DMN engines. However, LLMs, when generating structured XML outputs, often introduce formatting inconsistencies, such as missing attributes, incorrect nesting, or misaligned column structures. These errors primarily arise due to the probabilistic nature of LLMs, which prioritise fluency over strict schema adherence, leading to schema deviations that require manual correction (Estrada-Torres et al., 2024; Tam et al., 2024). One proposed solution is schema-aware prompting (Corea et al., 2019), which explicitly includes XML-based DMN templates in the prompt to enforce structural integrity. Additionally, format-restricting instructions and structured schema constraints have been shown to improve LLM compliance with XML-based decision tables. However, research highlights a trade-off between schema rigidity and reasoning performance, as excessively constrained generation can degrade the model’s ability to produce contextually appropriate outputs.

LLM-generated DMN tables must maintain logical consistency to ensure that rules do not contradict each other, cover all necessary conditions, and align with the specified decision logic. However, due to the stochastic nature of LLM outputs, generated decision tables often contain conflicting rules, redundant conditions, or missing dependencies, leading to inconsistencies in decision automation (Goossens et al., 2022). These logical

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inconsistencies are particularly problematic in domains where decision logic involves multi-variable dependencies and cascading rule applications. To address this, post-generation validation frameworks have been explored, enabling automated rule verification and conflict detection (Shorten et al., 2024). Some approaches integrate constraint-based verification systems, where generated DMN tables are analysed against predefined business logic constraints to ensure compliance. Additionally, iterative refinement techniques, where LLM-generated tables undergo secondary validation using rule-checking models, have demonstrated improvements in logical accuracy (Berkovitch et al., 2025).

A major limitation of LLM-generated DMN tables is hallucination, where the model produces non-existent or logically incorrect decision rule (Calvanese et al., 2018). Unlike traditional errors, hallucinations appear as plausible but fabricated rules, often leading to incorrect decision-making outputs. These errors occur because LLMs generate content based on statistical inference rather than direct retrieval of domain-specific knowledge, making them susceptible to introducing unsupported rules or fabricated dependencies (Li et al., 2022). To mitigate hallucination, retrieval-augmented generation has been proposed as an effective strategy, allowing LLMs to retrieve validated decision rules before generating outputs (Goossens et al., 2023). This method significantly reduces the likelihood of hallucinations by anchoring model outputs to pre-existing, verified decision logic. Additionally, schema-aware constraint injection has proven effective in minimising hallucinated rules in DMN tables (Tavantzis et al., 2023).

Complex formula generation is essential for DMN automation, as many decision models require mathematical computations and logical expressions rather than simple rule-based conditions (Bork et al., 2023). LLMs must not only generate syntactically correct formulas but also ensure they align with Friendly Enough Expression Language, the standard for DMN expressions (Leewis et al., 2024). However, maintaining both syntactic and logical correctness remains a challenge, as LLMs often introduce errors such as invalid syntax, missing dependencies, or logically inconsistent calculations (Liu et al., 2024).

Additionally, validation mechanisms play a crucial role in ensuring correctness (Goossens et al., 2023). Syntactic validation checks generated formulas against FEEL grammar rules, preventing syntax errors, while semantic validation ensures that computed outputs align with expected decision outcomes. By integrating these approaches, LLM-driven DMN automation can achieve more reliable formula generation, reducing the need for manual corrections and improving decision-making accuracy in real-world applications. Ensuring the correctness of LLM-generated DMN tables requires robust validation mechanisms to detect syntax errors, logical inconsistencies, and missing conditions (Liu et al., 2024). While manual validation is an option, it is inefficient for large-scale decision automation (Jeong, 2023). Research suggests that automated rule validation frameworks can significantly improve the reliability of DMN tables by systematically checking for structural completeness and logical soundness.

One approach to validation is formal verification, where decision tables are analysed using geometric representations and dependency graphs to detect overlapping or missing rules. Another strategy involves test case validation, where generated DMN tables are executed against sample datasets to verify that outputs align with expected decision outcomes (Funk, 2023). Combining these techniques with machine learning-based anomaly detection further enhances the accuracy and reliability of LLM-generated decision models.

Large Language Models have emerged as a transformative tool for automating the generation of DMN tables, enabling the structured representation of decision logic directly from natural language inputs (Bork et al., 2023). Traditional DMN modelling requires manual definition of input conditions, rules, and outputs, which can be both time-consuming and prone to inconsistencies. By leveraging LLMs, organisations can streamline this process, reducing manual effort while improving scalability and accessibility for non-technical users. However, despite their promise, LLMs face several technical challenges when applied to DMN table generation, including schema compliance, logical consistency, hallucination control, and complex formula generation. One of the primary obstacles in LLM-based DMN automation is schema adherence, as decision tables must conform to a strict XML-based format with predefined structures. Studies show that when LLMs generate structured XML or JSON outputs, they often struggle to maintain correct formatting, leading to missing attributes, incorrect clause definitions, or invalid hit policy assignments (Salinas & Morstatter, 2024). These issues arise because

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LLMs generate text probabilistically rather than following a rigid schema. Approaches such as schema-aware prompting and format-restricting instructions have been explored to mitigate these errors, ensuring better compliance with DMN standards (Etinger et al., 2019).

Another critical challenge is logical consistency, as DMN decision tables require non-contradictory, exhaustive rule coverage. LLMs, however, tend to introduce redundant or conflicting rules when generating decision logic, particularly in complex tables that require interdependent rules. Ensuring that generated DMN tables maintain logical soundness often requires post-generation verification through automated validation frameworks. Some research suggests integrating rule-based validation mechanisms that can automatically detect and resolve conflicts, improving the reliability of LLM-generated decision models (Goossens et al., 2023; Woensel & Motie, 2024).

To enhance decision accuracy and reduce hallucination, retrieval-augmented generation has been proposed as a method to ensure LLM-generated DMN tables align with verified decision logic (Calvanese et al., 2018). Instead of relying solely on generative inference, LLMs retrieve validated decision rules from existing datasets before generating outputs, reducing the risk of fabricated or inconsistent rules. Experiments indicate that integrating structured retrieval with generative outputs significantly improves the factual consistency of generated DMN tables, especially in domains where regulatory or business constraints dictate decision structures.

Beyond retrieval-based improvements, formula generation within DMN tables remains a key limitation for LLMs. Many decision models require computed attributes, such as calculating a credit score based on financial parameters or determining eligibility based on derived conditions (Leewis et al., 2024). LLMs, when prompted to generate formulas, frequently produce syntactically valid but logically flawed expressions. Methods such as multi-step decomposition, where models generate formulas iteratively rather than in a single pass, have shown promise in improving accuracy (Liu et al., 2024).

While these advancements improve the reliability of LLM-driven DMN generation, further challenges remain in scalability, adaptation to domain-specific constraints, and the ability to refine decision logic dynamically. Future research should focus on embedding rule validation directly into the generation pipeline, enabling LLMs to detect errors in real-time rather than relying solely on post-processing corrections (Jeong, 2023). Additionally, enhancing adaptive schema enforcement techniques and domain-specific fine-tuning will be critical for making LLM-driven DMN automation robust enough for real-world applications.

3. Background

This paper presents a series of case studies that illustrate the practical applications of DMN tables in automated decision-making processes. Each scenario highlights how DMN enables organisations to address specific challenges, such as streamlining operations, improving decision quality, and adapting to changing business rules. These examples demonstrate the versatility and effectiveness of DMN in diverse industries. By examining these case studies, we aim to showcase the potential of DMN tables to revolutionise decision-making processes, offering insights into their implementation and impact. The scenarios presented not only provide a deeper understanding of DMN's capabilities but also underline its importance in achieving scalable, efficient, and accurate decision automation.

Scenario 1. Automated University Admission Screening Using DMN Decision Tables
In this case study, we explore the application of DMN decision tables in automating the university admission process to filter applicants based on their academic performance. The DMN table evaluates students' qualifications based on their declared department and scores in specific subjects such as Math, Physics, and English, along with an optional criterion like a motivational letter score. The automation process leverages the "Automatic Decision" column to determine whether a student's application should be accepted, declined, or requires further clarification (Figure 1).

The workflow begins when a student submits their application, specifying the desired department and the scores achieved in relevant subjects. The system, using the DMN table, cross-references these scores against

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predefined criteria for each department. For instance, a student applying to the "Computer Science" department must meet a minimum score in Math or Physics to be considered, as shown in the rules of the decision table. Based on the table's calculations, an automatic decision is made, and the student is notified accordingly. This automated decision-making significantly reduces the workload of the admissions committee by eliminating the need to manually review applications that fail to meet minimum requirements or clearly qualify based on high scores. Students who do not meet the standards receive a rejection notification ("DECLINE"), while those who qualify are informed of the university's interest ("ACCEPT"). Applications requiring additional information, such as borderline cases or incomplete submissions, may trigger a request for clarification ("CLARIFY").

Students Acceptance Criteria | Hit policy: First

	When	And	And	And	And	Then
	Department (string)	Math (integer)	Physics (integer)	English (integer)	Geography (integer)	Automatic Decision (string)
1	"Computer Science"	< 138	–	–	–	"DECLINE"
2	"Computer Science"	> 180	> 170	–	–	"ACCEPT"
3	"Computer Science"	> 180	–	> 170	–	"ACCEPT"
4	"Physics and Astronomy"	–	< 145	–	–	"DECLINE"
5	"Physics and Astronomy"	> 160	> 185	–	–	"ACCEPT"
6	"Physics and Astronomy"	–	> 185	–	> 170	"ACCEPT"
7	–	–	–	–	–	"CLARIFY"

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Figure 1. Students Acceptance Criteria Table
Source: Own work

The implementation of DMN decision tables in this context demonstrates the potential to streamline university admission processes by focusing committee resources on complex cases that require human judgment. This approach not only enhances efficiency but also ensures consistency in decision-making. By automating routine evaluations and focusing on candidates who meet or exceed criteria, universities can maintain a fair and transparent selection process while effectively managing high application volumes.

Scenario 2. Automated Gift Selection for Customers
In this case study, we explore the application of DMN decision tables in automating the process of selecting gifts for customers based on predefined criteria such as birthdays, holidays, and the value of their previous purchases. The decision table is used to evaluate a customer's eligibility for a gift, making the process quicker and more efficient while ensuring consistency in how customers are rewarded (Figure 2).

Gift Selection for Customers | Hit policy: First

	When	And	And	And	Then	And
	Has Birthday Today (boolean)	Is Holiday Today (boolean)	Last Purchase Category (string)	Last Purchase Price (decimal)	Coupon Category (string)	Decision
1	true	false	"Electronics"	> 1000	"Celebrate the client!"	"10% discount on accessories"
2	true	true	"Any"	> 750	"Holiday appreciation"	"Free shipping on next purchase"
3	false	true	"Clothing"	> 1000	"Bring back the client"	"10% discount on all clothing"
4	false	true	–	–	"Remind the client"	"Special offer for the first purchase

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Figure 2. Gift Selection for Customers Table
Source: Own work

The process begins when their birthday or a holiday occurs. The system checks the customer's data, including the type of their last purchase, their spending amount, and whether today is a special day like their birthday or a recognised holiday. Using the DMN table, the system then determines which gift or promotional offer to provide based on the combination of conditions. After the table processes the input data, the "Decision" column provides an automatic decision: the customer either receives a special offer or is reminded about an exclusive promotion. For instance, if it's the customer's birthday and they purchased electronics worth over $1000, they

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might receive a 10% discount on accessories. If it's a holiday and the last purchase was any item over $750, they might be given free shipping on their next purchase.

This automated decision-making significantly reduces the workload on marketing teams, as it eliminates the need for manual gift selection. Customers who meet the criteria automatically receive a notification of their gift or offer, ensuring that the process is fast, efficient, and personalised. By automating these decisions, the business can focus resources on more complex tasks, while ensuring that customers who qualify for rewards based on simple criteria are quickly and consistently recognised.

Scenario 3. Alternative Program Recommendations for University Applicants
In this case study, we examine how DMN decision tables can automate the process of recommending multiple alternative academic programs to university applicants who do not meet the criteria for their first-choice program. This approach leverages the capability of DMN tables to generate multiple results, offering students a range of suitable options based on their academic profile and additional qualifications.
When a student submits an application, including their preferred program, academic scores in relevant subjects, and optional data such as motivational letter scores or extracurricular achievements, the system uses a DMN decision table to evaluate their eligibility across various programs. Unlike systems that return a single decision, the DMN table identifies all programs the student qualifies for and ranks them based on fit (Figure 3).

Alternative Program Recommendations for University Applicants — Hit policy: Rule order

	When	And	And	And	Then	And
	First-Choice Program (string)	Math Score (integer)	English Score (integer)	Extracurriculars (string)	Recommended Programs (string)	Reasoning (string)
1	"Computer Science"	< 160	–	"Tech Club"	["Information Technology", "Applied Computing"]	"Lower math requirement, strong extracurricular profile in technology."
2	"Engineering"	< 140	> 170	–	["Digital Media", "General Studies"]	"High English score aligns with creative and general education programs."
3	"Computer Science"	< 160	–	"Robotics Club"	["Applied Computing"]	"Relevant extracurricular activities compensate for lower Math grades."
4	–	< 140	< 140	–	["General Studies"]	"Does not meet specific thresholds, recommended for a broad foundational program."
5	"Computer Science"	> 165	> 185	–	["Information Technology", "Digital Media"]	"Strong English score and moderate Math performance suggest technical programs."

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Figure 3. Alternative Program Recommendations for University Applicants Table
Source: Own work

For instance, a student applying for "Computer Science" but failing to meet the Math requirement might receive recommendations for both "Information Technology" and "Applied Computing," especially if their extracurricular activities align with these programs. Similarly, a student with strong English skills but lower Science scores could be offered both "Digital Media" and "General Studies," giving them flexibility in choosing an academic path. This multi-result capability allows universities to provide applicants with personalised options while reducing manual evaluation efforts. By presenting a comprehensive list of alternative programs, along with explanations for each recommendation and clear next steps, the system ensures that students feel valued and supported. This approach demonstrates the flexibility and power of DMN decision tables in automating complex, multi-outcome decision-making processes.

In this scenario, the DMN decision table operates under the "Hit Policy: Rule Order", which ensures that all matching rules are evaluated, and their outputs are provided in the order they appear in the table. This approach is crucial for scenarios like alternative program recommendations, where the objective is to generate multiple results rather than a single decision. The "Rule Order" policy prioritises rules sequentially based on their placement in the table, allowing the system to rank recommended programs effectively. For instance, if a student qualifies for both "Information Technology" and "Applied Computing," the system lists them in the order specified in the decision table, ensuring transparency and alignment with the institution's priorities. This policy ensures that students receive a structured and prioritised list of alternatives, enhancing their ability to make informed choices while maintaining consistency in decision-making.

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4. Research Objective and Methodology

While LLMs demonstrate promising capabilities in generating structured DMN tables from natural language input, they often fall short in scenarios requiring domain-specific reasoning, derived attributes, or strict adherence to schema constraints. These limitations become especially critical in real-world applications where the correctness and completeness of decision logic directly affect operational outcomes.

The goal of our research was to evaluate whether integrating RAG can significantly improve the quality and accuracy of DMN table generation in such challenging scenarios. Specifically, we focused on a use case where the required decision attribute – Body Mass Index (BMI) is not explicitly present in the input data but must be calculated from available fields (i.e., weight and height). This setup tests the model's ability to reason over available context and apply transformation logic as part of DMN table construction.

By comparing the performance of a pure LLM pipeline against an LLM & RAG approach, we aim to answer two questions:

- Can RAG help the model recover relevant transformation logic and apply it correctly during DMN generation?
- Does this integration improve the validation pass rate when DMN output is tested against a domain-specific rule engine?

This research thus provides a focused assessment of schema injection and derived logic reasoning two core challenges in the automation of DMN modelling and serves as a benchmark for the effectiveness of retrieval-based enhancement in structured code generation.

To evaluate the impact of RAG on the quality of DMN table generation, we designed a controlled experiment that simulates a real-world decision-making scenario. The research was cantered around generating a decision table for BMI-level classification, where the target attribute (BMI level) must be inferred from other available data attributes – namely, weight, height, and gender. This setup challenges the model to not only generate syntactically valid DMN XML but also apply correct domain-specific logic for computing derived values.

We tested two approaches: a baseline using an LLM-only prompt and an enhanced variant where the same prompt was supplemented with a retrieval context (LLM & RAG). Both versions were evaluated by generating DMN tables from the same natural language instruction and validating them against a predefined set of 100 structured input objects. The goal was to assess whether the presence of retrieved background knowledge would improve rule completeness, accuracy of derived logic, and schema conformity. The experimental environment included automated validation using a DMN engine, allowing us to systematically quantify the success or failure of each generated table. This setup enabled a reproducible comparison of how well each approach handles non-trivial transformation logic and adheres to the structural requirements of DMN.

Input Data

The input for the experiment consisted of two core components: a natural language prompt describing the decision logic, and a set of structured test objects simulating real-world entity data. These inputs were designed to reflect realistic use cases in which decision logic must be inferred from partial or derived attributes rather than directly declared fields. The natural language prompt explained how to calculate a person's Body Mass Index based on their weight and height, and how to classify the resulting value into a corresponding BMI-level. The classification rules were gender-specific and covered overlapping and edge-case conditions. This prompt required the model to generate a decision table that includes an internal formula (BMI = weight / (height * height)) and conditional logic that adapts based on both numerical ranges and categorical gender values.

The entity objects were provided in JSON format and included attributes such as id (integer), first and last names (string), gender (string), weight (double) and height (double).

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Notably, these objects did not contain an explicit BMI value, thus requiring the model to understand that BMI must be computed dynamically before applying classification logic. A total of 100 mock entities were generated to cover a variety of valid and boundary-case scenarios (e.g., underweight, normal, overweight, obese), ensuring broad test coverage for each rule in the decision table. This design enabled testing not only for the generation of structurally correct DMN tables, but also for the model's ability to reason over entity properties and synthesise derived attributes when necessary. The test scenario was constructed to evaluate the model's ability to generate a complete and executable DMN decision table from natural language, especially when the required decision logic involves derived attributes. Specifically, the task involved classifying individuals into BMI-level categories based on computed Body Mass Index (BMI), which is not directly available in the input data. Figure 4 demonstrates the input sent to the model to generate DMN Table based on the rules.

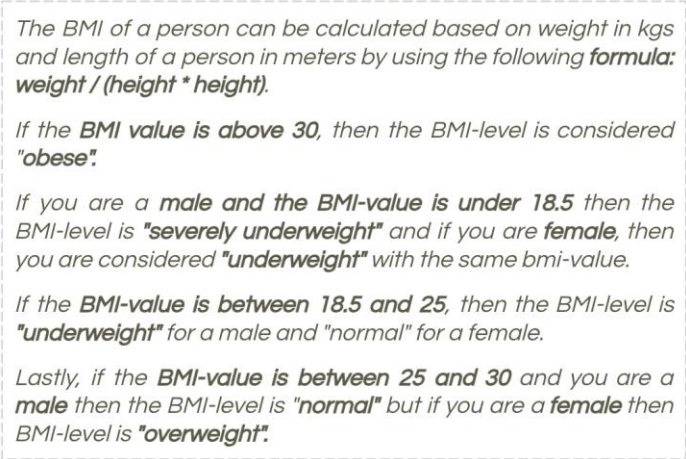


Figure 4. Test Input Data
Source: Own work

This scenario was executed across 100 test cases covering all possible branches of the logic. The experiment was repeated under two conditions: with LLM-only generation and with RAG-enhanced generation, allowing direct comparison of correctness and robustness across both settings.

Validation Strategy

To assess the correctness and robustness of the generated DMN decision tables, we implemented an automated validation pipeline based on rule execution over a predefined test dataset. This strategy allowed us to evaluate not only the structural integrity of the generated DMN XML code but also its ability to correctly classify input objects according to the expected logic.

The validation process involved the following steps:

1. **DMN Parsing and Deployment**. Each generated DMN table (in XML format) was parsed and deployed to a DMN engine capable of executing decision logic. Tables that failed to parse due to structural errors were marked as invalid immediately.
2. **Test Data Execution**. A set of 100 structured test objects was prepared in JSON format, each containing weight, length, and gender attributes. These inputs were executed against the deployed DMN table to compute the output column (BMI-level) for each case.
3. **Expected Output Comparison**. For each input object, the correct BMI value was precomputed, and the expected BMI-level classification was determined using the ground truth logic described in the prompt. The engine output was then compared against the expected result.
4. **Result Classification**. Each experiment run was classified as Passed if all 100 objects produced correct classifications and the DMN file was syntactically valid. Any mismatch in decision output or structural failure was marked as Failed.
5. **Metrics Reported**.
   - Pass Rate. Number of fully successful experiments divided by total attempts.

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- Failure Reasons. Categorised into structural errors (invalid XML), logical errors (incorrect rule application), or missing decision branches.

This validation strategy ensured that we could rigorously test whether the LLM understood the full semantics of the decision logic, handled derived attributes correctly, and generated DMN tables suitable for deployment in decision engines. Comparing results from both LLM and LLM & RAG runs enabled a quantitative evaluation of the impact of retrieval-based augmentation.

5. Results and discussion

The research was conducted under two configurations: using an LLM-only pipeline and using an LLM enhanced with Retrieval-Augmented Generation (LLM & RAG). For each configuration, 100 independent test runs were executed using the same natural language prompt and input schema. The goal was to compare the ability of each approach to produce a valid and correct DMN decision table that passes automated validation against 100 structured input objects. The results clearly demonstrate the performance improvement when retrieval support is added in Figure 5.

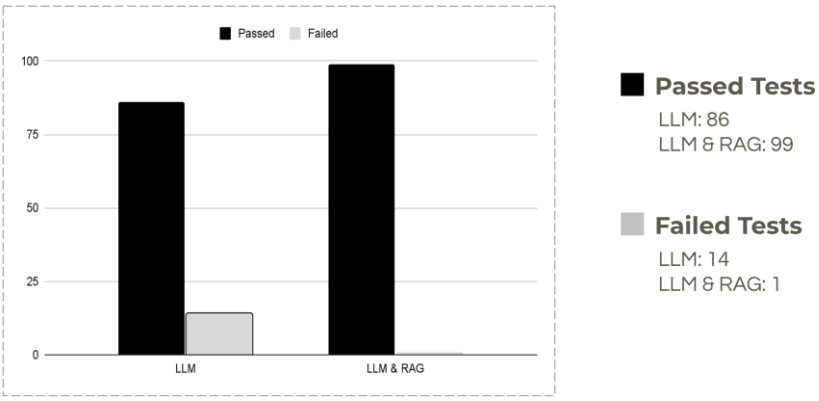


Figure 5. Test Results
Source: Own work

In the LLM-only setup, 14% of the generated DMN tables failed validation. Failures were primarily caused by:

- Incorrect or incomplete handling of BMI calculation logic.
- Missing classification branches (e.g., overlapping conditions or non-mutually-exclusive rules).
- Occasional syntactic issues in the generated XML structure.

By contrast, the LLM & RAG configuration achieved a 99% success rate. The addition of domain-specific retrieval (in this case, relevant logic for BMI calculation and classification) provided critical grounding information that allowed the model to:

- Correctly include BMI calculation as part of the decision logic.
- Apply all conditional branches with the appropriate gender-specific logic.
- Avoid hallucinated rules or structural omissions.

These results confirm that RAG significantly improves both logical completeness and structural correctness of the generated DMN tables. Moreover, the experiment highlights the value of retrieval, especially in cases where decision attributes are derived rather than directly present in the schema.

The experimental results highlight several important implications for the field of automated DMN table generation. First, they confirm that while LLMs are capable of producing structured decision logic from natural language, their reliability in non-trivial cases is limited without external knowledge grounding. The LLM-only configuration performed reasonably well on simpler cases but consistently failed in situations where reasoning over implicit schema relationships was required. This finding is consistent with earlier observations in the

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literature that LLMs tend to hallucinate missing logic or omit edge conditions when prompted without access to structured context.

In contrast, integrating Retrieval-Augmented Generation significantly improved the model's output by providing it with relevant procedural knowledge (e.g., the BMI formula and classification thresholds). This aligns with prior studies on RAG, which emphasise its role in reducing hallucinations and improving factual grounding in generative outputs. Importantly, RAG allowed the model to successfully apply transformations not directly encoded in the entity schema, addressing one of the core research challenges in DMN automation. Another key takeaway is the role of validation in structured generation tasks. Even when outputs appear semantically correct, subtle structural errors (e.g., overlapping rules, non-exclusive branches) can cause runtime failures in DMN engines. The experiment shows that without automatic validation, assessing correctness solely by manual inspection or LLM confidence is insufficient.

Overall, the experiment provides empirical support for a hybrid architecture combining LLMs with schema-aware prompting, retrieval mechanisms, and automatic validation. This architecture not only increases reliability but also paves the way for more complex, explainable, and verifiable LLM-driven decision automation pipelines. Future work should focus on generalising this approach to more diverse domains, formalising retrieval sources, and exploring integration with constraint-based validation tools. To assess whether the observed difference in accuracy between the LLM-only and LLM & RAG configurations was statistically significant, we applied a two-proportion Z-test. This test evaluates whether two independent proportions differ significantly, under the null hypothesis that they are equal.

We define the proportions of successful outputs as follows:

- LLM only. 86 successes out of 100 trials ($p_1 = 0.86$)
- LLM & RAG. 99 successes out of 100 trials ($p_2 = 0.99$)

The Z-statistic for comparing two proportions is calculated. Substituting the values: z = -3.49. The corresponding p-value is approximately 0.00048, which is well below the standard alpha threshold of 0.05. The result is statistically significant with $p < 0.001$, providing strong evidence that the improvement in performance observed with RAG is not due to chance. This supports the conclusion that retrieval-augmented generation contributes meaningfully to the accuracy and reliability of DMN table generation.

Proposed Framework

To address the complexity and manual effort involved in constructing DMN decision tables from natural language, we propose a modular framework that leverages the reasoning capabilities of LLMs enhanced with structured schema injection and domain-specific retrieval. The framework is designed to automatically convert textual descriptions of business rules into executable, validated DMN decision models. At its core, the system integrates five key components: a Schema Injector that provides contextual data awareness, a Retrieval Module that supplements missing background knowledge, a Prompt Composer that structures the full input for the LLM, a Generation Module responsible for producing DMN code, and a Validator that ensures the structural and logical correctness of the resulting model. Together, these modules form a closed-loop architecture capable of supporting both straightforward and derived decision logic. This design enables schema-consistent DMN generation with minimal human intervention and supports the transformation of natural language decision logic into robust decision automation artefacts.

Schema Injector

The Schema Injector is responsible for extracting and formatting structured information about the domain entity that will be processed by the DMN model. It collects the list of available input attributes and their types directly from the entity definition and prepares this information in an XML-based format compatible with the DMN context structure. This component does not perform any logical transformations or reasoning. Its sole purpose is to ensure that the language model receives an explicit and complete description of the input data structure. This includes only directly defined properties without interpretation or derivation. By doing so, the Schema Injector guarantees that the LLM has the necessary raw context to generate a DMN table that aligns with the actual structure of the input data.

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Retrieval Module (RAG)

The Retrieval Module enhances the generation process by providing the language model with access to external domain knowledge that may be required for accurate DMN construction. This includes background rules, classification thresholds, standard formulas, regulatory constraints, or any predefined business logic that is not explicitly stated in the user's prompt or the entity schema.

The module operates as part of a RAG pipeline, querying a curated collection of domain documents or rule repositories. Retrieved content is selected based on relevance to the task and appended to the model's input prompt. This augmentation enables the LLM to ground its outputs in verified knowledge rather than relying solely on its internal representation. By enriching the prompt with retrieved information, the Retrieval Module reduces hallucinations, improves coverage of edge cases, and supports consistent reproduction of formal decision logic that aligns with real-world standards or organisational policies.

Prompt Composer

The Prompt Composer is responsible for assembling all necessary input elements into a structured prompt that is submitted to the language model. It combines the user's natural language description of the decision logic, the structured entity schema from the Schema Injector, and the external knowledge retrieved by the Retrieval Module into a single coherent input.

In addition to merging these content blocks, the Prompt Composer also appends a set of explicit generation instructions. These include directives that constrain the language model's output to:

- Return only XML content.
- Generate a valid DMN-compliant decision table.
- Strictly follow the DMN XML specification without additional commentary or formatting artifacts.

This combination of structured context and instructional constraints is essential for achieving predictable, machine-executable output. The Prompt Composer ensures that all parts of the prompt are properly formatted and ordered, minimising ambiguity and improving the consistency and quality of the generated DMN code.

LLM-Based Generation Module

The LLM-Based Generation Module is responsible for transforming the structured prompt into a complete DMN decision table using a large language model. This module acts as a one-shot generator, producing the final output in XML format based solely on the prompt provided by upstream components. The model receives a prompt that includes:

- A text description of the decision logic.
- A formalised XML schema of the input entity.
- Relevant external knowledge retrieved from the knowledge base
- A set of strict generation instructions that define output format and constraints.

The prompt instructs the model to generate a DMN decision table that adheres to the official specification, with no additional text, explanation, or formatting outside of the required XML structure. The generated table must define:

- The input and output elements (matching the schema).
- A decision table with complete and mutually exclusive rules,
- Any internal logic necessary to handle derived attributes,
- Proper references to FEEL expressions where applicable.

The generation process is stateless and context-limited: the model has no memory beyond the provided prompt, which places high importance on the completeness and clarity of the input. The model itself does not validate the generated output, meaning that syntactic and logical correctness are not guaranteed without post-processing.

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This module is optimised for structured code generation and benefits from prompt engineering techniques such as few-shot examples, output formatting hints, and output delimiters. Its effectiveness depends directly on the combination of schema injection, relevant retrieval, and well-formulated instructions.

DMN Validator

The DMN Validator is responsible for evaluating the structural and logical correctness of the DMN table generated by the language model. It acts as an independent verification layer, ensuring that the output is not only syntactically valid XML but also semantically correct and executable according to the DMN standard. The validation process consists of several stages:

- **XML schema validation.** Confirms that the generated code adheres to the DMN XML specification and can be parsed by standard DMN engines.
- **Structural consistency checks.** Verifies that all referenced inputs, outputs, and decision rules are properly defined and connected.
- **Logical validation.** Applies the generated decision table to a predefined test dataset to confirm that the logic produces correct and complete outputs across all relevant cases.

The validator detects common issues such as missing rules, overlapping conditions, type mismatches, or undeclared input variables. It also supports the use of edge-case test inputs to confirm the robustness and generalizability of the generated logic.

Conclusions

This research presents a novel framework for automating the conversion of natural language descriptions into DMN decision tables, addressing the complexity and manual effort traditionally involved in constructing these models. By leveraging the reasoning capabilities of Large Language Models (LLMs) in conjunction with structured schema injection and domain-specific retrieval, we have developed a system capable of generating accurate, validated DMN decision models with minimal human intervention. At the core of this framework is a modular architecture that integrates five key components: a Schema Injector, Retrieval Module, Prompt Composer, Generation Module, and Validator. This system facilitates schema-consistent DMN generation, supporting both straightforward and more complex decision logic. The hybrid approach combining LLMs with schema-aware prompting, retrieval mechanisms, and automatic validation not only enhances the reliability and accuracy of decision model generation but also provides a pathway for more explainable and verifiable decision automation pipelines. Empirical evidence gathered from our experiments indicates that the integration of Retrieval-Augmented Generation (RAG) significantly improves the accuracy of DMN table generation. A statistical analysis using a two-proportion Z-test revealed that the performance improvements observed in the LLM & RAG configuration were statistically significant ($p < 0.001$), further supporting the conclusion that RAG contributes meaningfully to the accuracy and reliability of the process. In addressing the research questions, the study provides clear and evidence-based answers. First, the integration of RAG demonstrably enhances the accuracy and completeness of LLM-generated DMN decision tables, confirming its effectiveness in grounding model outputs in domain-specific knowledge. Second, the inclusion of schema injection and retrieval mechanisms proved instrumental in reducing structural and logical inconsistencies, ensuring that generated models adhere more closely to the DMN specification while minimising hallucinations and redundancy. Third, the proposed framework shows strong potential to support scalable, explainable, and verifiable decision automation, offering a robust foundation for integrating AI-driven reasoning into practical business decision-making environments.

These findings suggest that the proposed framework represents a promising step toward practical, explainable, and verifiable decision automation. It can serve as a valuable tool for organisations seeking to enhance the transparency, accuracy, and consistency of their decision-making processes. Building on the insights derived from this study, future research should extend the framework to diverse business domains, formalise retrieval sources for domain-specific reasoning, and integrate constraint-based validation mechanisms to further strengthen reliability and scalability in automated decision modelling.

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POSSIBILITIES OF USING UNMANNED AERIAL VEHICLES IN HEALTHCARE WITH AN EVALUATION OF THE BENEFITS AND THREATS*

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Abstract. This paper explores the potential applications of unmanned aerial vehicles (UAVs) in healthcare, focusing on their implementation in real-world scenarios. UAVs, commonly known as drones, have shown significant promise in improving healthcare services, particularly in the rapid transport of medical supplies such as blood, vaccines, and laboratory samples. Through a systematic review of existing literature, this study identifies five key areas where drones are already being utilized or hold potential for further integration: sample transportation, emergency medical services (e.g., AED delivery), organ transport, disaster relief, and mosquito population control. The study highlights both the benefits and risks associated with UAV deployment in healthcare, including increased efficiency and accessibility of medical supplies versus concerns over safety, battery life, and regulatory challenges. The paper concludes with an evaluation of the readiness of these technologies for widespread adoption, suggesting that with further improvements and regulatory adjustments, drones could become integral to modern healthcare systems.

Keywords: drones, economic efficiency; decision-making; healthcare; medical supply transport; emergency medical services; organ transport; disaster relief; mosquito population control

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JEL Classifications: J2, L1, G1

1. Introduction

Current demographic trends, such as a growing and aging population, are placing unprecedented pressure on healthcare infrastructure and delivery. While the number of patients requiring medical care is increasing, current systems are lagging behind in many areas, leading to long waiting times and inadequate diagnostics. In response to these challenges, modern technologies, including unmanned aerial vehicles (UAVs), are coming to the fore, with the potential to automate and streamline logistics processes. The main objective of this article is to search for and analyse available information on the commercial use of UAVs in healthcare and, based on the findings, discuss recommendations for their implementation in practice.

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The need for innovative solutions is most urgent in regions with low levels of infrastructure and health security, such as sub-Saharan Africa, where road transport often fails or is too slow for urgent cases. Drones can play a key role here not only in supporting the so-called SMART (Speed Metrics Automation Remote Technologies) laboratories and sample collection automation, but also in saving lives in crisis situations where minutes are crucial. The article therefore focuses on identifying real existing solutions, as well as on the results of scientific research in this area.

Based on a systematic review of the literature and analysis of available sources, five key areas in which the application of drones appears to be the most promising were identified: transportation of biological samples, transport of external defibrillators (AEDs), logistics in natural disasters, organ transport and mosquito population control. These areas are categorized in the work according to the degree of their technological readiness and real deployment, from theoretical concepts to systems fully implemented in practice.

In the following sections of the article, the current state in each of the five identified areas will be discussed in detail, while the work will focus on analysing existing problems and the ways in which the introduction of drones solves them. The discussion will then assess the main risk factors associated with these solutions, such as safety, legislative restrictions, and battery life. The conclusion of the paper will provide a synthesis of the findings and an assessment of the readiness of these technologies for wider adoption in modern healthcare systems.

2. Theoretical background

According to UN reports, there are well-known statistics that say that there is and will be a steady increase in the demands on healthcare provision and therefore on healthcare infrastructure. In particular, there are statistics on the constant population growth - the projected population in 2030 is 8.5 billion and 10.9 billion at the end of this century. At the same time, there are areas where fertility rates are as high as 4.6 live births per 1 mother. However, areas with high fertility are also areas with low infrastructure and low health security, such as sub-Saharan Africa (hereafter referred to as "SSA") The current health system is lagging behind the increasing number of patients who have to wait long periods of time to be examined and receive poorly comprehensive diagnoses (Mannello & Plebani, 2022).

Another worrying statistic is the constantly ageing population, which is once again increasing the number of patients who are referred for medical assistance. The UN reports that in 2018, for the first time, there were more people over 65 than children under 5 in the world. At the same time, by 2050, it is projected that there will be twice as many people over 65 as children under 5 in the world, and more of them than adolescents aged 15 to 24 (World population prospects, 2024).

Drones have found their use in a variety of fields and industries where they simplify, digitise and automate routine activities. One prominent area is healthcare, within which they are considered an integral part of laboratory healthcare for the decade starting in 2020. Drones could form part of so-called SMART laboratories to support their automation. The greatest potential is seen in the collection and transport of various samples taken from patients. (Mannello & Plebani, 2022; Shapira, 2025)

Within the scope of the paper, it will be analysed in more depth what areas within the healthcare sector present problematic issues and possible solutions need to be found. It will also analyse how the use of drones could help within those areas.

3. Research objective and methodology

The main goal of the paper is to search for available relevant information considering commercial usage of unmanned aerial vehicles (UAV) in healthcare. Based on our findings we discuss common recommendations for commercialization of these type of solutions. We have focused the search on two major areas: 1) real existing solutions; 2) solutions presented as results of science and research in relevant scientific databases.

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The process of creating the methodology consisted of 6 main steps. The first step was a search of available literature and publications on the topic of drones in healthcare using keywords such as "drones in healthcare", "drone capabilities", "drone usage". The scientific databases Scopus and Web of Science were used for the search. In addition to the keywords, a publication-year filter was applied. The search primarily targeted publications from 2021 to 2025 to reflect the most recent technological capabilities, regulatory developments, and real-world implementation of UAV solutions in healthcare. Older publications were included only in cases where they provided substantial scientific value (e.g., seminal or frequently cited evidence relevant to the research topic).

After collecting publications relating to the topic under study, each publication was sorted for suitability and relevance to the research in question. The sorting of publications was done in 2 phases. In the first phase, the abstracts of the publications were studied to assess their relevance to the research. The exclusion criterion in the first phase was also the availability of the full text of the publication. The full publications remaining after sorting from the first phase were studied in the second phase. The criterion for inclusion of a publication in the research was the identification of a link between UAVs and healthcare, i.e., the publication had to clearly define in which area UAVs were used/tested, for what reasons, and what the outcomes were - benefits and threats - from this.

In a third step, the publications thus sorted were grouped according to the areas of use identified in the publications. The fourth step then consisted of creating specific groups of areas in which the benefits of drones for healthcare were identified. Specifically:

- transport of samples,
- AED transport,
- natural disasters,
- organ transport,
- mosquito control.

The identified application areas have created scope for a deeper understanding of the use of drones with respect to a specific area. Therefore, in the fifth step, further information was tracked down to answer the following research questions:

- What is the current state (in terms of process, technology, personnel)?
- What are the resulting problems?
- How can the introduction of drones address the problems?
- Has anyone tried to introduce drones in the area to solve the problems?
- If drones have been introduced, how has this helped the status quo and conversely what other problems and issues has this brought?

Within the subchapters with research findings will be structured based on the 5 areas identified. The sixth and final step was to create categories for the extent to which the identified solutions have been put into practice, and so this will be a systematic classification into 5 categories according to the extent to which they have progressed in their development. The resulting rankings can be seen in Table 1, where category 5 represents the options with the highest degree of development. The categories are formed cumulatively starting with category 1, which represents the baseline. With each successive category with a higher number, development is rated as better. This means that any category contains all the developmental stages reached by all categories below it (with a lower number) and in addition has reached a new, further developmental stage. In category 2, clinical trials rep-resent a superstructure above experiments, as they mean that the technology has already been put into practice in a systematic way, but has not yet been officially launched as it collects and evaluates data from the pilot operation.

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Table 1. Classification of the uses of drones identified in the analytical part into 5 categories

Category	Category description	Examples of use
1	High application potential	General: transport of laboratory-produced organs for transplantation Specifically: • EHang + Lung Biotechnology PBC
2	Category 1 + studies known to have been carried out	General: transport of AEDs Specifically: • TU Delphi
3	Category 2 + experiments have taken place	General: transport of organs for transplantation, transport of AEDs, transport of specimens at city level, mosquito population control Specifically: • Matternet (Germany, Japan) - samples + medicines, • Everdrone (Denmark) – AED, • Flirtey (USA) – AED, • MedziDroid Project – spraying for mosquitoes, • Nguyen, Krupke, Burbage et al: Using a UAV for Destructive Surveys of Mosquito Population • Carrasco-Escobar et al. (2022). The Use of Drones for Mosquito Surveillance and Control. Parasites & Vectors • Gilmour & Hoff (2025). Drone-Assisted Organ Transport: A Scoping Review of Clinical, Regulatory, and System Readiness.
4	Category 3 + clinical trials have taken place	General: transport of AEDs Specifically: • Everdrone (Sweden) – AED, • Zipline (USA) – vaccines.
5	Category 4+ system is in place and implemented in practice	General: transport of medical supplies (medicines, vaccines, blood, samples for analysis), mapping of areas devastated by natural disasters Specifically: • Zipline (Rwanda, Ghana) – blood + medicines, • Matternet (Switzerland, USA) – samples, • Nepal, • Haiti, • Philippines, • Vanuatu.

Source: composed by the authors, based on Karpstein (2024), Tudelf (2025), Swiss Post (2022), Kolodny (2017), Schierbeck (2023), Everdrone (2020), Dukowitz (2020), Mechan (2023), Nguyen et al. (2018), Carrasco-Escobar (2022), Gilmour (2025), Zipline (2021), Zipline (2025), Edwards (2024), Alfaris (2024), Yucesoy (2025), Bhattacharya (2025), Rattanaamporn (2025)

In the next chapter (results), the domains will be described in order of the category. Within the description of each area, attention will be paid to the description of the current situation and the problems associated with it, options for addressing the current situation, examples of deployment in practice, and the results of deployment in practice.

4. Results

As results we will provide main important information from our search. We present the results with the use of the structure of 5 identified areas of use within the healthcare.

4.1. Transport of samples

In most cases, only small laboratories are set up at the sites where physical sampling is carried out, covering basic tests that are not intended for bulk processing. Comprehensive diagnostics are carried out in large stand-alone laboratories equipped to handle large numbers of samples with a wide variety of types of tests. It is necessary to transport the collected samples from the collection site to the designated laboratories at regular intervals. An example of the ratio is provided by statistics from the United States, where small clinical

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laboratories accounted for approximately 75% of the total number of laboratories, but covered only about 13% of the total tests performed. (Ong, 2022; Shapira, 2025; Stierlin, 2024)

It is possible to consider 2 main directions of solution. The first brings transport via drones and the second via aerial drones. The question with drone transport is to what extent such transport can be safe and whether the samples will not be degraded during flight due to acceleration, braking or changes in temperature and air pressure. However, studies have shown that the transport of biological samples by drones is safe and does not degrade them so that clinical out-comes remain unaffected. However, for a successful deployment of a UAV network in practice, it is necessary to take into account the climatic conditions and test each type of sample individually. Thus, transport of samples is possible but requires adaptation to the conditions of the area. (Nisingizwe, 2022; Wiltshire, 2024)

A pneumatic tube system is similar to a UAV in that it offers fast and efficient transport. It has the advantage of ease of use and safety, but requires a complex network of tubes and appropriate software to avoid collisions. The disadvantages are the high cost of compressed air and sensitivity to vibration. However, the main problem is that this system is only usable within buildings or between closely spaced buildings, as the external tubes are susceptible to damage and take up a lot of space. It is inefficient for connecting larger complexes (Swisslog Healthcare, 2025).

There are 2 known deployments in practice, namely by Zipline and Matternet, both cases with different intentions. Zipline uses centralized warehouses for the distribution of health supplements over the largest possible distances. Matternet, on the other hand, transports samples from health collections within the community over short distances. Due to the purpose of transportation, the solutions also use different types of drones - Ziplnine uses fixed-wing drones and Matternet uses multi-propeller drones. In both cases, speed and safety are important criteria.

Zipline has partnered with the government in Rwanda to create the world's first commercial medical device delivery service via drone. The transport network mainly provides transportation of blood packages, vaccines and various medicines (Zipline, 2025). Road communication is slow and health facilities routinely find themselves running short of various supplies, especially blood. In the event of an emergency, the blood supply can take several hours to arrive, which can have fatal consequences. Blood is important in a variety of emergencies, such as massive haemorrhage in childbirth, which has long been identified as the leading cause of mortality among women in pregnancy (Figo, 2025), with the highest incidence of cases in central and sub-Saharan Africa (Unicef Data, 2019). Another important link is vaccines. For health workers working in rural areas, their storage at low temperatures as well as maintaining the necessary stock levels is a significant problem (Zipline, 2021). Zipline's solution has been actively helping to reduce the statistics of female mortality starting in December 2016, when Ghislane was rescued and became the first person in the world to owe her rescue to a UAV (Zipline, 2021). Overall mortality rates may have dropped by 38%, but 295,000 deaths in 2017 is still a high number, not to mention that deaths caused by bleeding in childbirth are easily reversible and one might even say unnecessary. (Unicef Data, 2019) Thanks to Zipline's solution, vaccines are stored in optimal conditions, and when needed, healthcare workers receive the necessary amount of refrigerated vaccines, allowing them to attend to patients without having to worry about supplies. (Zipline, 2021) Additional evidence of Zipline's global success can be seen in its entry into several new countries. These include Arkansas since 2021, and Utah, Côte d'Ivoire, Nigeria, Kenya and Japan since 2022. Their growth has extended beyond healthcare. With UAVs rede-signed for urban settings, Zipline has also begun exploring deliveries in the fields of gastronomy and agriculture (Insider Intelligence, 2023).

Switzerland, in collaboration with Matternet Inc. ("Matternet") and the national post-al service Swiss Post, has decided to connect hospitals and laboratories using autonomous UAV devices. These drones are able to load and unload cargo, take off, and land autonomously. The autonomy and safety of the process are ensured by three-meter stations, introduced in 2020, which allow drones to fly without direct contact with humans. Deliveries are made via QR codes, allowing them to be used even in hospitals without dedicated staff. The drones have transported biological samples for rapid diagnosis, such as biopsies during tumor surgery, or blood in emergencies when the hospital ran out of supplies (Swiss Post, 2022). Matternet also operates in the US and,

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as of November 2020, is operating in Germany, where it is working with Labor Berlin Charité Vivantes on the EU's first urban medical drone network without visual surveillance. This network connects 3 organizations and can significantly reduce sample transport time and increase lab efficiency (Suas News, 2020). The company is also expanding into Asia in partnership with Japan Airlines from September 2020, where it will transport medicines and medical supplies between Mediceo's ware-house and St. Luke's Hospital in Tokyo. Since the launch of the drone network in 2017, approximately 3,000 successful deliveries have been made. (Brian, 2019) The drone is a multirotor with 4 propellers, is capable of carrying 2 kilograms, has a range of 20 kilometres, and flies at a speed of approximately 36 km/h. (Kolodny, 2017; Molinary, 2024) Swiss Post stated that they have been able to reduce delivery times by up to 45 minutes by using drones. (SWI Swissinfo.Ch, 2020) In addition to time, costs have also been reduced because various ground transport services, such as taxis, as well as emergency ambulances, have been used for emergencies. Andreas Raptopoulos, founder of Matternet, stated that by re-placing emergency vehicles with drones, hospitals can save 20% to 50% of transport costs (Swiss Post, 2022). In January 2019, there was a delivery failure when a drone made an emergency landing on Lake Zurich. Investigation revealed a GPS failure due to a short circuit, but the emergency mode worked properly. In April, operations were restored, but in May another incident occurred in which the parachute ruptured and the drone crashed. Although it did not injure anyone, it highlighted the safety risk (Brian, 2019). Operations were suspended for half a year, and in January 2020 Swiss Post and Matternet introduced new security measures. (Norman, 2020.) The drones did not return to service until late August 2020 after a pandemic hiatus. (Apex Insight, 2020)

4.2. AED transport

The importance of resuscitating a patient before the arrival of emergency services is shown in different studies, for example from Sweden by authors Hasselqvist, Riva, Herlitz (2015). They observed data from 30,381 out-of-hospital cardiac arrest cases using the statistical variable "30-day survival rate", which is used in medicine to show survival rates 30 days after an incident. In the study, cardiac arrest is considered an incident. They found that 51.1% of patients received resuscitation before the arrival of emergency services and their survival rate was 10.5% as opposed to patients who did not receive resuscitation and their survival rate was 4%. In addition, they also found the effect of time on the onset of resuscitation performance with the results shown in Table 2 showing that with each minute of not giving resuscitation, the probability of surviving the incident drops sharply. (Hasselqvist-Ax, 2015; Lafrance, 2023; OECD, 2025; Jensen, 2023)

Table 2. Impact of time on survival rates in resuscitation delivery.

Time to resuscitation	Survival rate
within 3 minutes	15,6 %
4 - 8 minutes	8,7 %
9 - 14 minutes	4,0 %
more than 14 minutes	0,9 %

Source: Hasselqvist-Ax, 2015; Lafrance, 2023

However, in addition to resuscitation, a publicly available defibrillator can also play an important role before the arrival of an ambulance. A study also published by The New England Journal of Medicine, where the object of investigation was Japanfound that 10.3% of people in cardiac arrest out of 43,762 studied received defibrillation, with a survival rate of up to 38.5%. The authors also point out that the survival rate after cardiac arrest with favourable neurological sequelae has also in-creased due to the currently freely available defibrillators. The interest of competent organisations in this direction can be seen, for example, in the form of guidelines from the European Resuscitation Council, in which they point to the statistic that defibrillation within 3-5 minutes of the incident will increase the survival rate up to 50-70%. They therefore call for the implementation of publicly available defibrillators, especially in places with a high density of people (Perkins, 2021; Katasako, 2023).

On the other hand, studies point to the under-occupancy of these devices in public areas. For example, a study from the Netherlands highlighted the problem that up to 60% of the placed automated defibrillators were not

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visible and only 88% of the devices were ready for use (the remaining ones either had a dead battery or were expired, a combination in the case of the latter) (Kim, 2022). Also, the Philadelphia study indicated that 70-80% of the devices were positioned such that in the event of an incident the estimated distance was a 3-minute walk (Grigoryan, 2025).

Given the potential for increasing survival rates in cardiac arrest with an automated defibrillator, it is worth considering the possibility of transporting such a device to the incident site in the event that none is present. Drone transport, which is independent of road infrastructure and traffic density, enters into consideration as the fastest transport. Much of the research into the practical use of drones in this area has been carried out in Sweden. One study found that in urban areas, the drone arrived at the scene of an incident faster in 32% of the cases, reducing the overall waiting time for help by 1.5 minutes. In rural areas, the drone arrived faster up to 93% of the time and the total time saved was 19 minutes. Such results are encouraging for further consideration to implement a drone defibrillator transport solution. (Schierbeck, 2023; Jakobsen, 2025)

In the second study, 2 different times were experimentally investigated: the first was the time from the emergency call to the departure of the device (ambulance, drone), and the second was the time from the departure of the device to its arrival at the incident site. 18 operations were performed and the median of the measured values was taken as the final time. The first initial time was 3 minutes for the rescue service, and 3 seconds for the drone, and the second time was 22 minutes for the rescue service and 5 minutes and 21 seconds for the drone (Fischer, 2023; Schierbeck, 2023; Jakobsen, 2025). Real deployment examples include Everdrone, Flirtey and TU Delphi.

According to Everdrone, 275,000 are hit by cardiac arrest in Europe every year with a survival rate of just 10%, and every minute without help reduces the likelihood of survival by 10%. Their system is available to 80,000 residents who, in the event of an incident after calling for first aid, await the arrival of a drone to reach the scene sooner, in addition to the arrival of the ambulance service. The defibrillator is brought to the ground from a height of 30 meters, from which it is lowered down by a rope. This method is quite innovative, as there are known tests of dropping the defibrillator from different heights or landing the drone with the defibrillator on the ground. Mats Sällström, CEO of Everdrone, claims that they have carried out a number of tests to find the most suitable method, which is precisely the gradual descent from a height argued by the danger of landing the drone close to humans. (Everdrone AB, 2020) The company takes particular pride in the safety of its devices, which is why they have also become one of the few companies that can carry out drone operations in populated areas and fly over people. (Intel Corporation, 2021) In June 2020, a test run of the system was launched. However, no results have been published from the company as of 2021, despite Mats Sällström's expectation that they would be published in January 2021 (Dukowitz, 2020). However, a smooth testing process can be assumed as the company has announced cooperation with Copenhagen Emergency Medical Services in 2021, thus creating room for expansion into Denmark. A delivery network covering more than 100,000 people in areas with long emergency services response times is planned to be launched in the autumn of 2021. Mats Sällström believes in a permanent roll-out of their solution in Sweden. Also, through innovations in technology, processes, or route planning optimization, they will build an efficient and robust solution not only in Sweden but also in Denmark (UAS Vision, 2020; Jager, 2021). Another drone food delivery company that has decided to take its business into the healthcare industry and deliver defibrillators to people is Flirtey Inc. The company teamed up with REMSA Health to create an emergency medical service in the US state of Nevada based on the statistic that cardiac arrest is the leading cause of death in the US (Schierbeck, 2023). In 2019, the FAA permitted them to operate flights outside of visual surveillance (Dukowitz, 2019).

Alec Momot is working on an ambulatory drone project that would incorporate various first-aid medical devices, which would include a defibrillator. He has designed a prototype of the drone, which has been given the name TU Delf. When the emergency ser-vices are called, a drone capable of communicating with the surrounding area would arrive at the scene. Thanks to a built-in microphone, speaker, and camera, the paramedic can navigate while administering first aid (Tudelf, 2025).

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4.3. Natural disasters

A sporadic but very appropriate use of drones is in natural disasters and catastrophes, in which drones can figure in various ways. In the event of an accident, a drone or group of drones can be sent to the affected site to gather important information about the extent and severity of the damage. Drones can scrutinize the surface and produce 3D maps that are evaluated to provide key information about the most affected areas. This will then allow rescuers to be sent to the places where it is really needed. Once these areas have been identified, medical supplies, food, or water can be delivered to people in need until rescuers arrive. The advantage of tracking the affected area by drone immediately after a disaster is to ensure the safety of people who would normally have to explore many areas in person, putting them at potential risk. Drones were used for this very purpose in Nepal after the magnitude 7.8 earthquake in 2015. In addition to mapping, the drones also contained thermal cameras that were able to identify where people in need of help were located. Using high-zoom lenses, they were able to recognize people's faces from over 300 meters away (Alfaris, 2024; Yucesoy, 2025).

Drones have also been used by the International Organization for Migration since 2012 to monitor 7 camps and their populations in Haiti. Drones were also used after Hurricane Sandy, which killed at least 54 people. After the storm was over, the drones immediately started mapping the environment and had the results 7 days before the first photo was taken by satellite. In collaboration with the OpenStreetMap community, before and after images were then compared to the floods to identify the hardest-hit areas that needed the most help. Historical satellite imagery was added to this data to create a prediction of the locations at greatest risk of future flooding. 3D maps were also created to identify hazardous river reaches used for infrastructure planning and flood protection for densely populated areas (Edwards, 2024). An example is the Philippines, which in 2013 experienced one of the worst typhoons, killing more than 6,000 people and was named Haiyan. The damage was extensive and the whole situation required additional aid. This was provided by SkyEye, with custom built drones locating survivors and assessing the extent of the damage, providing in-sight into possible prioritization of aid (Bhattacharya, 2025).

Another example is the small island of Vanuatu, which suffered significant damage after Cyclone Pam, and 75 000 people were made homeless. National Geographic researcher Patric Meier went to the country on assignment as a crisis cartographer and launched the UAViators programme, which is now a widespread humanitarian drone organization whose mission is to promote the safe, effective, and humanitarian use of drones in a variety of areas. Drones at that stage were mainly used to assess the repairability of houses, as aerial and satellite imagery could not detect all the damage. With this data, they were able to determine the need for funding and the places worth re-pairing. They used a crowdsourcing method to evaluate the vast amount of imagery, where they posted the images online and had volunteers analyse them. Quality control was ensured by showing 1 shot to even 10 people for analysis, which they could afford given the large number of volunteers (Humanitarian UAV Network, 2021; Rattanaamporn, 2025).

Among the most important results of the deployment can be considered the possibility of a quick analysis of the affected area. The UAV can be sent to the site immediately after a natural disaster, regardless of the safety conditions of the affected area, and assess the current status and extent of the damage. This enables rescue forces to make better decisions on how to rescue. Technologies that make it possible to accurately locate survivors are also a major advantage. Based on this, it is possible to send emergency responders to where they are needed. In addition to analysis, UAVs can also be used to deliver life-saving resources such as water, food, and medical supplies until rescue forces arrive on the scene.

4.4. Organ transport

As many as 169 million people in the U.S. registered as donors in 2019, according to statistics from Organdonor, the main federal organization overseeing the nation's trans-plant system. Despite the abundance of donors, organs are still in short supply due to which people are dying every day. Many organs are even lost unnecessarily and inadequate transportation is cited as one of the causes. Organs last only a short while in strictly controlled conditions after removal from the donor and often ambulances, helicopters or planes have to be used to transport them, which is a costly option. (Karpstein, 2024) The integration of drones into the donated organ transport network could be a solution. This topic is actively addressed by Gilmour & Hoff (2025) who have also experimentally investigated the impacts of kidney transport by drone. The concern was in the disruption of

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fragile human tissues due to drone vibration and applied pressure. However, the results of the biopsies showed that drone transport did not damage the kidney under study.

Similar penetration can be seen in the case of the collaboration between EHang, a company focusing on aerospace technology, and Lung Biotechnology PBC, a company specializing in the production of lungs and other organs for transplantation using advanced technologies. The companies have agreed on a 15-year collaboration to use EHang's 184 drone, which was the world's first autonomous drone capable of transporting a human. The EHang 184 is to be converted into a drone designed exclusively to transport organs for transplantation under a programme called the Manufactured Organ Transport Helicopter System. This ambitious project has generated attention and anticipation (Karpstein, 2024; Gilmour, 2025).

4.5. Mosquito control

In tropical areas such as sub-Saharan Africa, there are mosquito species that carry dangerous diseases such as malaria, chikungunya disease, dengue fever, lymphatic filariasis, West Nile virus disease, or yellow fever. Management of the mosquitoes that transmit them is essential to control integrated diseases. Different authors working at various institutions focused on tropical diseases, microbiology, parasitology, or immunology, have also provided in-sights on this issue. In their publications, the authors discuss various types of diseases occurring in tropical areas, where they attribute their lack of control largely to poor infra-structure and poor staffing of sampling sites and laboratories. The biggest gaps they see are in sub-Saharan Africa, where poor diagnostic infrastructure was evident in the 2014-2015 failure to contain and subsequent outbreak of Ebola. For mosquito management, the spraying method is commonly used. Such indoor and outdoor spraying uses manual ground spraying from a portable backpack sprayer or the more costly and therefore less available and used aerial spraying (helicopter, aircraft). Current spraying using human labour is considered by the project authors to be very inefficient, as these sprays in many cases need to be done on difficult to access terrain with poor climatic conditions, which pose a potential risk of various injuries and direct exposure to disease. At the same time, such spraying requires regularity and precision in the amount of spray chemicals applied, which is not achieved by human factors and leads to wastage (Kitonsa et al., 2020; Mechan, 2023; Ndlovu, 2025).

At the same time, tracking is also used for mosquito population management. Tracking individual mosquitoes is challenging due to their small size, unpredictable flight patterns, and preference for low-light environments. To address this, researchers have conducted tracking studies in confined indoor areas (approximately 4 by 8 feet) or by observing mating swarms against simple backdrops. The primary method for monitoring mosquito populations remains stationary traps, which require weekly inspections, such as encephalitis vector surveillance traps and gravid traps. Although efforts are being made to develop smaller, more cost-effective traps that provide real-time data, these approaches still depend on attracting mosquitoes into the traps. (Nguyen, 2018; Carrasco-Escobar, 2022) Sub-Saharan Africa, although a region of weaker socio-economic development, is subject to the interest of foreign investors. The last decade has been accompanied by the realization that technology can play a key role in the development of SSA, and drones may be one such technology. SSA is on the verge of a technological revolution due to the influx from developed countries (Karpstein, 2024).

According to the World Health Organization (WHO), the systemic solution is based on 3 core components: site surveillance, a coordination center, and a national laboratory. Improving laboratory networks has become an international concern for several countries in recent years, and an important partnership, the Global Health Security Agenda (hereafter "GHSA"), currently composed of 69 countries, NGOs, and private companies, has emerged, which has established 3 pillars for ensuring framework health: prevention of disease outbreaks, early detection of threats, and rapid response. The authors emphasize that new technologies, including UAV devices that provide rapid and efficient transport of biospecimens to laboratories in locations with poor infrastructure, have a very important role to play in meeting the pillars and prerequisites (Kitonsa et al., 2020; Ndlovu, 2025).

Potential solutions include the MedizDroids Project, which aims to find a sustainable and affordable solution using UAV technology based on the automation of indoor residual spraying, outdoor residual spraying, and larval source control. The MedizDroids Project is developing a solution that could replace the currently used spraying methods through multiple drones, which are expected to cost between €85 and €420. The automation of interior spraying involves spraying the interior and exterior walls of living spaces to kill adult mosquitoes

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that use these spaces for resting or feeding. The automation consists of 3 stages, where in the first stage (preparatory) households are mapped and the necessary sensors are placed. In the second stage, the actual spraying takes place starting with each wall until every household is covered. In the third stage, the success of the spraying is to be investigated by monitoring the premises. The actual spraying would then take place by having the drone accurately map each dwelling with its walls and floors in advance and then, according to a set schedule, enter the dwelling through the entrance and systematically spray all walls, floors, and ceilings, and finally leave the dwelling at the end (Mechan, 2023).

As part of the optimization of traps using UAVs, there is the possibility of using electrical discharges. This topic was addressed by Nguyen, Krupke, Burbage et al, who aimed to design a UAV capable of systematically destroying mosquitoes. The authors also created a pilot model to test the solution. A custom-built six-armed drone was used as the UAV, in which the Pixhawk autopilot flight controller and ArduPilot Mega flight software were employed. The board consists of 2 aluminum mesh panels separated by a 3-millimeter gap. These are protected around the perimeter by fiberglass rods to ensure that the mesh is not damaged when the drone lands. After the overall construction, the net, weighing 0.948 kg, provided an effective area of 0.161 m2 (Nguyen, 2018; Carrasco-Escobar, 2022).

Several tests were performed to properly adjust the UAV (especially the position and inclination of the mesh), including monitoring the airflow in the wind turbine. In addition, the authors also proceeded to experimental verification of functionality. The authors chose an area of 120m x 15m on which they performed 8 autonomous flights with predefined routes during different parts of the day. During each flight, the possibility was provided to manually take control of the drone in case of any failure or unexpected situations. At the same time, each flight was recorded audiovisually, which also served to verify the number of discharges. The experiments yielded significant findings, especially in terms of localizing the occurrence of mosquitoes during the day and night. They were found to be most active in the early morning and early evening and to have their highest concentrations in areas with trees. As pointed out by the authors themselves, such test flights alone can significantly help to understand where mosquitoes occur and at what times and in which places they do not occur. The study refers to other possible means of control, such as traps mimicking human bait or genetically modifying mosquitoes to reduce their reproductive capacity or ability to transmit disease. Another method currently used is insecticides, which, although inherently effective, are a burden on the planet in the long term and mosquitoes are gradually building up resistance to them (Nguyen, 2018; Carrasco-Escobar, 2022).

5. Discussion

Drones represent a significant contribution to healthcare, particularly in the area of rapid delivery of medical materials such as medicines, samples and blood products to remote or hard-to-reach areas. Their use can speed up diagnostic processes, improve ac-cess to healthcare and reduce logistics costs. With further advances in technology and improvements in security measures, drones have the potential to transform the efficiency and quality of healthcare services worldwide. We state five main risks factors of the analysed solutions. The 5 areas of the potential use of drones in healthcare analysed are associated with similar risks that they carry. For this reason, the risks for all 5 areas are presented together.

Security and safety
The biggest risk of using drone networks is their security. Drones can weigh between a few kilograms and 20 kg, and dropping them from a height of, say, 100 meters poses a risk of injury. Although there are no reported fatalities with commercial drones, minor injuries such as scratches or bruises do occur, with the most serious being damage to the eye. A 2019 study by the ASSURE organization examined the impacts of drone collisions on humans, with only one out of 512 tests resulting in a visible skull injury in a high-speed collision. The research results suggest that drones are made of flexible materials that can absorb much of the energy of a collision. Drones today use sophisticated safety systems, including 3D mapping, intelligent route planning, emergency landing, and obstacle avoidance sensors. For example, Intel's advanced RealSense technology, which can detect both stationary and moving objects (Perz, 2024; Ní Aoláin, 2023; Kusnirova et al., 2024; Staffenova et al., 2025; Svatý, 2025).

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The airspace
Another risk is a collision with another UAV, which can be difficult to predict and avoid, as drones can fly at speeds of up to 100 km/h and sensors may not be able to detect an object moving at such speeds. Zipline solves these problems with a patented system based on decentralized monitoring centres that communicate with drones. The UAV devices contain sensors that monitor the surroundings and send the data to a center that adjusts the flight trajectory. The drones also share information about obstacles so that other devices can optimise their routes. For example, if one drone encounters a thunderstorm, the other drones may choose a different route. Before taking off, each drone must get permission and has an optimal route calculated based on a 3D map, including elevation movements (Lendel et al., 2021; Hamissi, 2023).

Contamination
The transport of biological material such as blood is a risk in itself, as there is a risk of contamination of the environment if the equipment fails and collapses. This problem was addressed, for example, by Amukele et al. (2015) in their study testing the possibilities of transporting blood by drone. They reported that blood samples for diagnostics were classified as potentially infectious biological material, requiring packaging in 3 layers so that in the case of liquids, the packaging had an absorption capacity 2 times greater than the material being transported (Amukele et al., 2015; Shapira, 2025; Miciak et al., 2025).

Battery life
As outlined above, the battery is one of the biggest obstacles to full UAV deployment as it is responsible for range capabilities. Many transportation network solutions using drones call for the use of multi-rotor types, which are very energy intensive to operate. Therefore, a trade-off has to be made between the weight of the equipment (and therefore the potential cargo) and the flight time. If the main concern is to have the longest possible range, the lowest possible payload must be taken into account, and if the main concern is to carry more weight, the transport must be carried out over a short distance. Improving UAV battery life can be achieved in a number of ways, such as using lightweight materials to reduce the weight of the device or planning routes with a minimum of turns that are energy intensive. Another option is to swap a dead battery for a charged one at strategic locations or to set up stopovers for recharging. An interesting proposal was presented by Huang et al. in 2019, where the drone uses public transport for part of its route, thus saving energy. Using long-distance lines, trains or logistics vehicles could also be a solution (Huang et al., 2019; Cokyasar et al., 2021; Demjanovicova et al., 2021).

Legislation
The biggest constraint to putting drones into practice is state legislation. Restrictions can vary from country to country. Generally speaking, restrictions can be placed on flying over populated areas, spraying any chemicals and dropping objects. These legislative re-strictions can be overcome with proven safe technology. An example of countries that have issued such permits for the commercial operation of drones, and a significant mile-stone is the granting of permission for drone flights over populated areas in Germany, as the first European Union country to do so.

5.1 Limitation
When interpreting the presented results, it is necessary to take into account several limiting factors that could have affected the scope and depth of this study. The first significant limitation was the set time frame and the number of researchers involved in the project. Limited personnel capacities reduce the time available for detailed research, which may lead to some specific aspects of the issue not being examined as thoroughly as would be desirable in the ideal case.

The second fundamental limitation is the chosen methodology, which relied exclusively on content analysis of available sources. Although this method provides valuable theoretical data, it can be considered one-sided, as it does not allow for direct interaction with the elements of the studied system. The study could have yielded more comprehensive and diverse results if it had been supplemented with other research methods, such as questionnaires or in-depth interviews with practitioners.

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The absence of empirical fieldwork and the reliance on secondary data may affect the general applicability and accuracy of the conclusions in the dynamically changing health technology environment. These factors suggest that while the study provides a strong theoretical overview, further research with a broader methodological scope would be needed to fully validate the proposed solutions.

6. Conclusions

The aim of this article was to analyse the available information on the commercial use of unmanned aerial vehicles (UAVs) in healthcare and assess their readiness for implementation in real practice. Through a systematic literature review from the Scopus and Web of Science databases, we identified key areas of application and categorized them according to their level of technological and process development. The methodology included not only a theoretical analysis of benefits and threats, but also the creation of a five-category classification system that made it possible to assess whether the solutions in question are only at the experimental stage or are already systematically used.

The results of the analysis confirmed that drones represent a significant benefit for healthcare, especially in the area of rapid transportation of medical supplies to hard-to-reach areas. Of the five areas studied, the transportation of laboratory samples appears to be the most developed, where there are already functioning commercial solutions. High application potential has also been confirmed in the transport of AEDs, where drones can radically shorten the response time in case of cardiac arrest, and in the management of natural disasters, where they are used for mapping and distributing aid. On the other hand, areas such as organ transport or mosquito population control require further verification of safety and effectiveness. However, implementation encounters barriers, which are mainly legislative restrictions, air traffic safety and battery life limits.

The evaluation of the analysed solutions will be presented, highlighting their strengths, weaknesses, and potential for future application. First is transport of samples. The use of drones to transport samples between healthcare providers and laboratory diagnostic providers is very realistic. Solutions exist, capacity is expanding and more providers are entering the market. Demand is coming mainly from states, regional and municipal governments. Solutions should be deployed in places where there is a lack of sufficient transport infrastructure and, conversely, in places where traffic is heavy with an increasing trend. Typical examples of the former are some regions in Africa, typical examples of the latter are densely populated urban agglomerations. In this case, UAV-based solutions represent a fast and relatively safe mode of transport. The biggest challenge here is the effective airspace management and overall safety of the deployed solution.

Second is AED transport. Time plays a critical role in the provision of emergency medical assistance, especially in circulatory arrest conditions where even a few minutes can mean permanent brain damage or a person becoming unresponsive. The response time of ambulance providers is limited by several factors, including the length of the route to the patient or the traffic situation. At the same time, the availability of an AED can be a critical factor in rescuing a person with a heart attack, and since most of these cases occur in the home, an AED is usually not available. A drone can bring the AED device to the patient at a breakneck time compared to the arrival of the medical service, and with the use of a system to lower the AED from a height without landing the drone, the safety of such acts is also increased.

Third is natural disasters. Drones have also proven themselves in practice in natural disasters, where they can be sent into areas that could potentially be dangerous for humans. At the same time, they can bring necessary commodities such as water, food, medicine to survivors before rescuers can reach the site. In addition, they can help identify areas where survivors are located so that rescue forces can be utilized efficiently to the places where they are really needed.

Organ transport is fourth. Within organ transport, drones can reduce transport time, increasing the chances of delivering undamaged organs in the right time. For deployment, the effects of transport on organ integrity need to be investigated.

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Five is mosquito control. The systematic destruction of mosquitoes and the management of their population is an increasingly debated topic. Drones can be used to apply sprays to areas that are difficult for humans to reach. At the same time, drones can apply the spray efficiently - mapping which areas to spray and which not to and counting the correct amount of spray, thus reducing spray wastage. At the same time, other methods of destruction, such as electric plates, can also be used.

The direction of further research should focus on overcoming the limitations of this study, which was based primarily on a content analysis of the literature. Future work could enrich the knowledge with primary data obtained through questionnaires or interviews with practitioners, which would provide a more comprehensive view of the issue. From a technological point of view, it is essential to investigate the impact of vibrations and overload during flight on the integrity of sensitive biological materials, such as organs for transplantation. It will also be important to monitor developments in the field of legislation and safety systems, which are key to the widespread integration of drones into modern healthcare systems.

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THE IMPACT OF SUSTAINABLE DESIGN ON RESIDENTIAL PROPERTY VALUES: ECONOMIC IMPLICATIONS FROM THE CZECH HOUSING MARKET

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Abstract. Sustainable design has become an increasingly important element of residential real estate development, yet its economic effects remain ambiguous across different market contexts. This paper examines the impact of sustainable design on residential property values in the Czech Republic, with particular attention to whether sustainability-oriented features translate into measurable price effects under real market conditions. From the perspective of sustainable development and investment decision-making, understanding whether sustainability generates economic benefits is crucial for investors, developers, and policymakers. The study is based on a dataset of residential property listings and applies standard statistical methods to examine the relationship between sustainable design features and market value. The analysis focuses on the independent effect of sustainability as well as its interaction with key market factors such as location and floor area. The results indicate that sustainable design alone does not function as an independent price driver in the residential housing market. However, when combined with traditional valuation factors, particularly location and property size, sustainable design features are associated with statistically significant differences in market value. These findings suggest that the economic effects of sustainability are context-dependent rather than universal. The paper provides relevant implications for sustainable investment strategies, housing policy, and decision-making processes in residential real estate markets, highlighting the importance of aligning sustainability objectives with local market conditions and economic feasibility.

Keywords: sustainability; sustainable design; market value; real estate; sustainable investment

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1. Introduction

With sustainability and environmental issues coming to the fore, sustainable design is becoming a key element in many industries (Katafygiotou et al., 2023). Sustainability is also an important trend in residential building design and there is an emphasis on energy efficiency and the use of environmentally friendly materials. In the context of the real estate market, sustainable design is thus an important factor that influences not only the attractiveness but also the market value of real estate (Goh et al., 2022). Residential properties with sustainable features are increasingly preferred by buyers who are aware of their long-term benefits. These benefits include lower operating costs, improved indoor environmental quality and greater resilience to climate change. Sustainable technologies such as solar panels, heat recovery systems or smart home systems are becoming not only the standard but also a desirable feature that can increase the value of a property on the market (Massimo et al., 2022).

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The market value of residential properties is therefore increasingly influenced by whether and how sustainable design elements have been implemented in their construction or renovation. While traditional criteria such as location or size remain important factors, sustainable aspects are playing an increasingly important role in the decision-making of potential buyers (Lambourne, 2022). This is creating a new dynamic market where sustainable properties are in greater demand and may command higher prices in some markets than their conventional counterparts. At the same time, this trend creates opportunities for developers and investors who can focus on projects that meet sustainable design principles. Evidence suggests that sustainable properties are more profitable in the long term and have a higher market value, which strengthens their attractiveness in a competitive market. As a result, sustainable design is becoming not only a responsible approach to the future, but also a strategic advantage in residential real estate (Goh et al., 2022; Warren-Myers, 2022).

Sustainable design, which focuses on minimising negative environmental impacts and using resources efficiently, is becoming increasingly important in the construction industry. This approach not only promotes environmentally responsible practices but also brings economic and social benefits (Katafygiotou et al., 2023). One of the key issues that arise in relation to sustainable design is its impact on the market value of real estate. Although it is widely accepted that sustainable architecture can reduce operating costs and improve quality of life, there are still concerns about the higher upfront costs associated with implementing these features (Toivonen, 2021).

Despite the growing interest in sustainable design, there are still relatively few studies that quantitatively assess its impact on residential property prices. (Rathnayake & Pushpakumara, 2023). This may be due to the complexity of the real estate market, where the price of a house is not only determined by its design, but also by its location, availability of services, the economy of the region and the overall demand (Massimo et al., 2022). However, sustainable design can provide a competitive advantage in the form of increased energy efficiency, lower operating costs, and increased occupant comfort, factors that are increasingly becoming critical in housing choice (Dobrovolskiene et al., 2021).

In the context of sustainable entrepreneurship and regional economic development, investments in sustainable housing represent an increasingly important segment of real estate markets. However, the economic outcomes of sustainability-oriented design are not always straightforward and depend on local market conditions, investor awareness, and traditional valuation factors. This study contributes to the debate by examining whether sustainable design features translate into measurable market value effects and under which conditions such effects emerge. The results are relevant for investors, developers, and policymakers seeking to promote sustainable housing without creating unrealistic market expectations.

The increased demand for sustainable real estate leads to the research objective of determining the impact of sustainable design on the market value of residential real estate. To meet the research objective, two research questions were posed.

Buyers often look for properties that offer energy efficiency, reduced operating costs and a positive environmental impact. This shift in preferences, coupled with legislative standards aimed at improving the energy efficiency of buildings, raises the first research question:

RQ1: Does sustainable design affect the market value of residential properties?

In examining the impact of sustainable design on the market value of residential property, it is necessary to consider other factors that may influence this relationship. For example, the location in which a property is situated plays a key role in determining its value; some areas may have a higher demand for environmentally friendly solutions than others. Similarly, the size and floor area of a property can influence how sustainable features are perceived by buyers. Given these variables, a second research question arises:

RQ2: How does the impact of sustainable design on the market value of residential properties vary depending on other factors such as location or floor area?

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2. Literature review

Sustainable design in the context of residential real estate focuses on creating living spaces that are environmentally friendly, economically viable and improve the quality of life of their occupants (Samour et al., 2023). Sustainable features such as green roofs and walls bring a range of environmental, social and economic benefits that improve building performance and contribute to the urban environment (Manso et al., 2021). Emphasis is also placed on the design of buildings that promote natural lighting and ventilation, thereby improving indoor microclimates and reducing energy costs. In addition to environmental aspects, sustainable design focuses on creating quality of life through healthy and comfortable environments, which may include the use of low-emitting materials and the design of spaces that promote social interaction and community life. This integrated approach not only contributes to the conservation of natural resources, but also increases the longterm value of properties and responds to the growing demand for sustainable and responsible residential solutions (Jalaei et al., 2020; Richter et al., 2022).

The impact of sustainable design on the market value of residential real estate is becoming an increasingly significant factor influencing the decisions of buyers, investors and developers alike (Dobrovolskiene et al., 2021). Properties designed with sustainability in mind, incorporating energy efficient technologies, renewable energy sources and environmentally friendly materials, not only contribute to lower operating costs but also increase occupant comfort and health (Aydin & Mihlayanlar, 2020). This positive impact translates into a higher demand for such properties, which often leads to an increase in their market value (Joshi et al., 2020). Moreover, with the increasing emphasis on environmental responsibility and legislative requirements, properties with sustainable design are perceived as less risky investments, further enhancing their attractiveness in the market (Tang et al., 2021). As a result, sustainable design is becoming not only a key element of modern architecture, but also a strategic advantage that can significantly influence the financial return on residential real estate investment (Ringel & Capeluto, 2020).

Although the importance of sustainability is increasing, its consideration in valuation practice is still insufficient and inconsistent, requiring further development and standardisation of methods (Warren-Myers, 2022). The valuation of sustainable elements is also addressed in Hossain et al. (2023). The research identified that although some valuers do incorporate sustainability in valuations, there is a lack of standardised methodologies and a consistent approach.

Leutner et al. (2024) investigates whether green buildings that are more energy efficient obtain more favourable terms in commercial financing compared to conventional buildings. The results show that green buildings have a lower interest rate and a lower target rate. However, no effect on the loan-to-value ratio was found. These findings suggest the financial benefits of investing in sustainable real estate. The issue of energy efficiency valuation is dealt with in Warren-Myers et al. (2020). Valuation of energy efficiency is often inconsistent and depends on different factors, making it difficult to accurately and fairly reflect these aspects in the market value of real estate. Korol and Shushunova (2022) focus on the valuation of energy efficient residential buildings that use innovative modular green walls. The integration of green walls significantly improves energy efficiency and increases the attractiveness and value of these buildings in the real estate market. Leskinen et al. (2020) investigates how on-site renewable energy production, for example by photovoltaics, affects property values. According to them, the presence of on-site renewable energy has a positive effect on property values. This effect has been attributed not only to energy cost savings but also to increasing awareness of the environmental benefits.

Cortesi et al. (2022) investigated the impact of sustainable property design on the comfort of its residents. The research found that sustainable architectural features such as energy efficiency and the use of natural materials have a positive impact on the psychological and physical well-being of residents.

For an analysis in which it is necessary to effectively compare means between multiple groups and identify whether statistically significant differences exist between them, we can use ANOVA (Kim, 2022). Another statistical method we can use is the chi-square test. Study Shen et al. (2022) shows that this test can be used to

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detect correlation based on the distances between data points, which is useful when analysing the impact of different sustainable features in different locations or for different property types. This flexibility makes the chi-square test a method for examining dependencies that are not always directly apparent but can still have a significant impact on the market value of properties. To better understand the relationships between factors and their impact on the market value of properties, we can use cluster analysis. This allows us to identify natural groups in the data based on the similarity of their characteristics (Kondruk & Malyar, 2021).

Despite the growing body of literature examining sustainability in residential real estate, several gaps remain evident. Existing studies primarily focus on individual aspects of sustainability, most notably energy efficiency, or rely on specific indicators such as green certifications, while often neglecting the combined effect of sustainability-oriented design features under real market conditions. Moreover, empirical evidence remains fragmented across different national and regional contexts, with limited attention paid to Central and Eastern European housing markets, where market maturity, buyer awareness, and valuation practices may differ substantially from those in more frequently studied regions. In addition, many studies assess sustainability effects in isolation, without sufficiently considering their interaction with traditional valuation determinants such as location and property size. This study addresses these gaps by empirically examining whether sustainable design features translate into measurable differences in residential property values in the Czech housing market and by analysing how their effects vary when combined with key market factors.

3. Methodology

The objective of the study is not to develop a predictive pricing model but to identify statistically observable relationships between sustainable design attributes and residential property values in a specific market context. A market analysis was carried out to answer both scientific questions. First, a database was created from the real estate server Sreality.cz. Listings were collected from publicly available advertisements on Sreality.cz between August 2024 and October 2024. Duplicated advertisements were removed to avoid repeated observations across listings. By analysing the text of advertisements from this server, data on family houses and development projects for the construction of family houses were collected, taking into account only properties with the energy label A (extremely energy-efficient) for the relevance of the comparison. All observations meet the A energy label criterion; therefore, sustainability in this study refers to additional explicitly stated sustainable features (e.g., photovoltaics, heat recovery, green roof, passive-house elements) beyond the energy label itself. The samples were distributed throughout the whole Czech Republic to create a sufficiently comprehensive database. For all samples, information was also recorded on their price, floor area, land area and identification of whether the property was sustainable and what specific sustainable element was present.

The first method used was the collection and analysis of data from advertisements on the real estate server Sreality.cz. The data were analysed only on this server because the advertisements on different real estate servers are often repeated and would then lead to data distortion. Data collection was done manually. Subsequently, the entries were recorded in a list, with information on their price, usable area, land area and identification of whether it was a sustainable property and what specific sustainable feature was present for each entry.

Subsequently, a one-factor analysis of variance (ANOVA) was used to assess differences in mean values between groups of properties with different levels of sustainable features. ANOVA was applied to test the hypothesis of equality of means between multiple groups and was used to determine whether the differences between these means could be considered statistically significant. The null hypothesis (H0) in this case assumed that there was no statistically significant association between property price and the presence of sustainable features, i.e., that the differences between the average prices were random. In this research, a significance level of 5% ($\alpha = 0.05$) was chosen.

A Chi-square test was then performed to answer the RQ2. The Chi-square test is a statistical method used to test the relationship between two categorical variables. Its main objective was to determine whether there was a significant relationship between these variables (in this case, the presence of sustainable elements and location) or whether they were independent. The test was based on a comparison of observed and expected values in a contingency table and assessed whether differences between them could be attributed to chance. The initial null

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hypothesis (H0) assumed that there was no statistically significant association between the variables. In this research, a significance level of 5% (α = 0.05) was chosen.

$$x^2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (1)$$

Where: x^2 is the chi-squared value of the test, O_i is the observed value, E_i is the expected value, ∑ means the sum over all categories or cells in the table.

In the next stage of the analysis, an extended ANOVA was conducted to include property location as a variable in addition to sustainable elements. This approach allowed the assessment of whether location affected the differences in property prices along with sustainable elements, and whether interactions could be identified between these factors. In a follow-up phase, another variable was added to the model – the usable area of the properties. In this way, it was possible to take into account not only environmental aspects and location, but also the size of the property, which is an important factor influencing its market value.

A cluster analysis was then performed. This method allowed the classification of properties into homogeneous groups that exhibited similar characteristics, which facilitated the analysis of patterns in the market data. Cluster analysis was used to examine the interrelationships between factors such as sustainable design, location and property size. The analysis included visualisation of the clusters, allowing for easier interpretation of the results and identification of market segments that may have specific needs and preferences.

4. Results

First, a database of residential properties was created to serve as the source of information for all other methods. A total of 134 single-family homes and single-family home development projects were registered, all with an energy label of A - extremely energy efficient.

Table 1. Sample overview

Continuous variables		
Variable	Mean (SD)	Min - Max
Asking price (CZK)	13 628 606 (5 877 665)	4 625 000 - 39 950 000
Floor area (m²)	160.5 (64.9)	75 - 550
Land area (m²)	639.7 (431.9)	49 - 3686
Categorical variables		
Variable	n (%)	
Prague area	33 (24.6)	
Other localities	101 (75.4)	
Specific sustainable feature stated in listing	73 (54.5)	
No additional sustainable feature stated	61 (45.5)	
Type of stated sustainable feature (among listings with stated feature)		
Feature type	n (%)	
Photovoltaics	35 (47.9)	
Heat recovery	34 (46.6)	
Energy-efficient	20 (27.4)	
Green roof	7 (9.6)	
Passive house	5 (6.8)	

Source: own study

Table 1 above summarises the basic characteristics of the analysed sample, including property prices, size, location structure and the prevalence of sustainable features. The dataset exhibits substantial heterogeneity in both price levels and property size, which supports the use of group-based statistical methods in subsequent analyses.

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To answer the first research question, an ANOVA was conducted. The results of the ANOVA analysis indicate that the calculated p-value is 0.148, which is above the established significance level of 5% ($\alpha = 0.05$). This result leads to the acceptance of the null hypothesis (H0), which states that there is no statistically significant relationship between property price and the presence of sustainable features. This means that the differences in house prices in this case cannot be attributed to the influence of sustainable elements and are more likely to be random rather than showing a statistically significant association with this variable. From an economic perspective, this result suggests that sustainability alone does not function as an independent price driver in the residential housing market.

Subsequently, analyses were conducted to answer the second research question.

A Pearson chi-square test focused on the association between location and sustainability. The results of the chi-square test show that the calculated p-value is 9.421e-05, which is significantly lower than the established significance level of 5% ($\alpha = 0.05$). This result suggests that the null hypothesis (H0), which assumes that there is no statistically significant relationship between the categorical variables analyzed, must be rejected. Based on these results, the alternative hypothesis (H1), which confirms the existence of a statistically significant relationship between the variables under study, can be accepted. This result indicates that the relationship between the variables is statistically verifiable and cannot be considered random.

The results of the second ANOVA analysis confirm this relationship and show that both sustainable elements and location have a statistically significant effect on property price. In this case, the p-values suggest that the differences in house prices can be attributed to the combined effect of these two factors. That is, both the presence of sustainable features and the location of the property play a role in shaping its market value, and this relationship is not random but statistically demonstrable. This result confirms the importance of both environmental factors and property location for the real estate market.

The results of the third ANOVA analysis confirm that, in addition to sustainable features and location, the usable area of a property plays a significant role as another factor influencing its price. The p-values show that usable floor area has a statistically significant effect on the market value of properties, and its inclusion in the analysis contributes significantly to explaining price differences. In this way, it can be concluded that all three variables - sustainable elements, location and usable area - together constitute the key factors that have a statistically significant impact on property prices.

The cluster analysis showed how the properties group together based on their price and floor area, see Figure 1.

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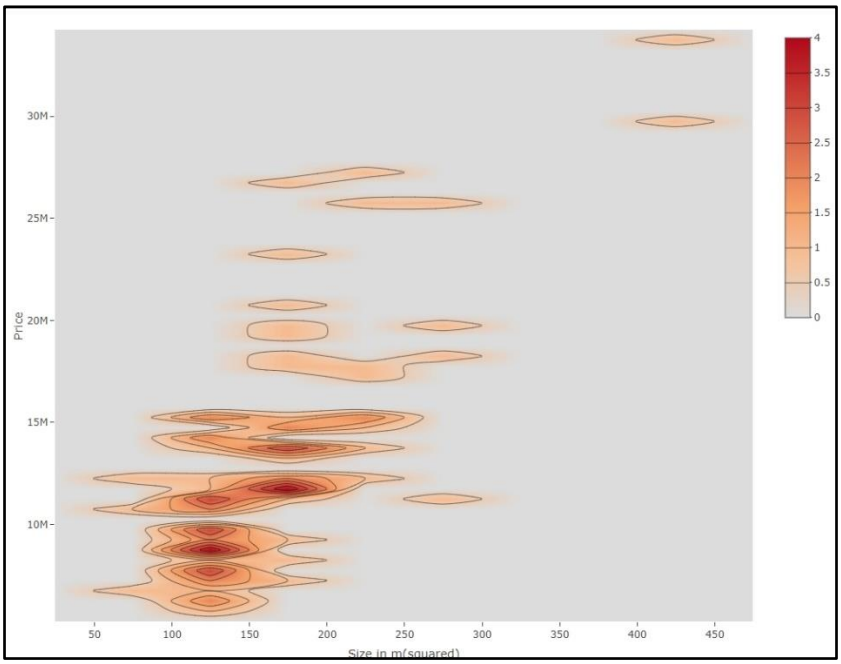


Figure 1. Cluster analysis results

Source: own study

The horizontal axis shows the usable area, while the vertical axis represents house prices. This analysis reveals different segments of the market, and individual clusters may indicate specific categories of properties that exhibit similar price and space characteristics.

The colours in the chart correspond to the density of data in each area, with darker red areas indicating a higher concentration of properties with given parameters, while lighter shades indicate a lower density. The chart shows that there are several distinct clusters that may indicate specific market segments.

- Smaller houses with a lower price (around 50-150 m² and CZK 5-15 million): this segment probably represents ordinary family houses with a smaller area, which are more affordable.
- Medium-sized houses (150-300 m²) with prices around CZK 10-20 million This segment is characterised by larger family houses with average prices. Most properties are concentrated in this area, which may mean that this category represents the most common offer on the market.
- Larger properties (300-450 m²) with prices above CZK 20 million These clusters indicate more luxurious properties that are larger and significantly more expensive.

Although the cluster analysis was primarily focused on property prices and floor area, it is important to note that the resulting clusters also reflect complex interactions with the presence of sustainable features and location. These factors are not isolated but interact and contribute to the overall market value of properties. For example, location can play a key role in what sustainable features are in demand in the market and can also influence the price of a property. In this way, the clusters provide a comprehensive picture of how sustainability trends are manifesting themselves in the property market and allow the identification of specific segments that may be sensitive to a combination of these factors.

5. Discussion

The findings address both research questions and can be summarised as follows.

RQ1: Does sustainable design affect the market value of residential real estate?

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Research has shown that the existence of the sustainable element alone does not affect the market value of residential properties in this case. Compared to the results of our study, where there was no statistically significant effect of sustainable design on the market value of residential properties, there are different perspectives on this issue within the current research.

Katafygiotou et al. (2023) looked at how sustainable design and awareness of it affect the real estate market. Their study shows that awareness of the benefits of sustainable design among buyers and investors is key for sustainable features to be perceived as adding value. In regions where this awareness is lower, the impact of sustainable features on market value is not significant. This result is consistent with our finding of no significant effect of sustainable design on market value. In our market, the lack of significant awareness and demand for green solutions may explain why market price was not affected by the presence of sustainable features. Why in some cases sustainable features do not lead to higher property prices could be explained by the results of the research Leutner et al. (2024). The research suggests that while sustainable buildings may have lower operating costs and energy savings, banks and investors may value these benefits less, leading to lower financing - i.e. a 'green discount'. There may be some scepticism on the part of financing institutions or buyers that prevents sustainable elements from being fully integrated into property valuations.

RQ2: How does the impact of sustainable design on the market value of residential properties vary depending on other factors such as location or floor area?

Our results clearly showed that the impact of sustainable design on the market value of residential properties varies significantly depending on other factors such as location and floor area. The analysis of the combination of these variables led to the conclusion that their synergistic effect contributes to the increase in the market value of properties with sustainable features. Our findings suggest that sustainable features gain in value mainly in certain locations or when specific property characteristics such as usable area are taken into account, which is in line with several other studies focusing on market valuation of sustainability.

For example, the study Warren-Myers (2022) highlights that sustainable element are priced differently according to market conditions, local regulatory frameworks and market awareness. In some regions or locations where sustainability is more integrated into valuation practices, higher 15 values for properties with these features can be observed, which is consistent with our finding of the increasing influence of location on price. Further Lambourn (2022) mentions that in some countries where sustainable construction is just developing, the impacts of these factors may be more pronounced. These observations suggest that taking into account local factors, such as local preferences for sustainable housing, can significantly alter how sustainable features affect property prices. This result resonates with our finding that locality plays a key role in how sustainable features are valued.

Further support for this thesis comes from research Khodabakhshian and Toosi (2021) who focused on life-cycle cost-based real estate valuation using Building Information Modelling (BIM). The study showed that long-term savings associated with sustainability can increase the value of real estate if properly calculated and included in the overall economic valuation. This confirms our finding that the value of sustainable properties increases when combined with other factors such as floor area - for example, larger spaces can benefit more from energy savings and other advantages of sustainable solutions, which in turn increases their value.

Our results can also be placed in the broader context of research such as Leskinen et al. (2020) which found that the impact of renewable energy on real estate increases depending on the specifics of the region and the type of property. The combination of sustainable design with factors such as usable floor area can deliver greater value where the demand for energy efficiency and sustainable living is stronger. This is in line with our findings, where a significant synergistic effect of sustainability, location and usable floor area on the market value of properties has been demonstrated.

Overall, our results confirm that the impact of sustainable design on property prices is not unambiguous and is strongly dependent on other factors. When analysing the relationship between the market value of properties

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and sustainable features, it is essential to take into account local market conditions, the usable area of the property and other specific characteristics that may influence this relationship.

The results indicate that sustainability-oriented investments in residential real estate should not be evaluated in isolation. For investors and developers, this implies that sustainable design features generate economic value primarily when aligned with location-specific and market-based factors. From a policy perspective, the findings suggest that promoting sustainable housing requires targeted and context-sensitive instruments rather than assuming uniform price premiums for sustainable features across regions. This has important implications for sustainable entrepreneurship, where investment decisions must balance environmental objectives with economic feasibility.

6. Conclusions

The aim of the research was to find out how sustainable design affects the market value of residential properties. The results show that the research objective was met. ANOVA, chi-square analysis and cluster analysis were used to meet the objective. This research can be beneficial to real estate agents, investors and developers, or owners and potential buyers of residential properties. It may also be beneficial to academics and researchers who would like to build on or extend this research.

The analysis has shown that the presence of sustainable features alone does not automatically lead to an increase in the market value of the properties. This result underlines the fact that the contribution of sustainability to property values is not always clear-cut. In practice, this may mean that sustainable technologies and design features are not perceived by buyers as decisive in determining price unless they are supported by other relevant factors. This finding is in line with some existing research that shows a limited direct impact of sustainability on property values, although these elements are often considered beneficial for the future life and running costs of buildings.

However, on deeper analysis, we found that when sustainable features are considered in conjunction with other factors such as location or floor area, their impact on market value changes significantly. This shows that while sustainability alone may not always influence price, when combined with factors that traditionally shape the property market, it can have a significant impact. In particular, the location and floor area of a property play a key role in determining its ultimate value. This is consistent with views that the property market is multi-dimensional and that combining sustainable elements with conventional factors such as geography and property size have a greater impact than a stand-alone sustainability assessment. The cluster analysis subsequently provided a comprehensive picture of the market structure, suggesting that similarities in market value and floor area are also intertwined with the presence of sustainable features and location. The results therefore show that these aspects are not isolated, but complement each other and together influence the overall value of the properties. This finding has important implications for future research and for property valuation practice, where sustainable elements should always be considered in a broader context. A limiting element of the research was the relatively small sample size of the sample studied. A larger sample set would have reflected reality in more detail, but despite this limitation, the results provide valuable insights into the relationship between sustainable design and the market value of residential properties. Thus, this paper contributes to the understanding of the potential economic benefits of sustainable features in the context of market valuation. In conclusion, sustainable design has the potential to influence the market value of real estate, but only in conjunction with other factors that have a key influence on the market. Although sustainable features alone may not always lead to an increase in value, their synergistic effect with factors such as location and floor area can have a significant impact. This study thus provides important insights for the real estate industry, investors and other professionals involved in property valuation and sustainability.

The study demonstrates that the economic effects of sustainable design in residential real estate are context-dependent. For sustainable entrepreneurship and housing policy, this implies that sustainability objectives should be integrated with traditional market mechanisms rather than treated as independent value drivers. The findings highlight the need for informed investment strategies and region-specific policy approaches that support sustainability while maintaining economic viability.

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The novelty of this study lies in its empirical examination of sustainable design features within a real market setting, demonstrating that sustainability does not operate as an independent price driver in residential property valuation but rather exerts its influence through interaction with traditional determinants such as location and floor area. By focusing on observed asking prices and explicitly stated sustainable features, the study provides evidence that the economic effects of sustainability are context-dependent and cannot be assumed to generate uniform market premiums. From a practical perspective, the findings offer relevant implications for real estate investors, developers, valuers, and policymakers. The results suggest that sustainability oriented design choices are most likely to contribute to market value when aligned with location specific demand and property characteristics, rather than being implemented in isolation. This insight supports more informed investment decision making, realistic valuation practices, and targeted housing policies that integrate sustainability objectives with local market conditions and economic feasibility.

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SUSTAINABLE ENTREPRENEURSHIP AND DIGITAL LEGITIMACY IN EUROPEAN UNION

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Abstract. The construction of the European Union's "digital single market" faces a paradox: improved availability of digital public services and infrastructure coexists with lagging uptake of mandatory digital administrative and compliance procedures by small and medium-sized enterprises (SMEs). Based on the European Interoperability Framework (EIF), this article reconstructs interoperability across different national legal jurisdictions and administrative systems as a market access condition and advocates for the proposal of "Institutional Middleware" as an interpretive mechanism to reveal how digital legality generates operational barriers and process inefficiencies at the legal/organisational level. Methodologically, this article adopts multi-source evidence design: firstly, we build the "Adoption Gap" index to quantify the gap between government service availability and enterprise usage rates; secondly, we combine e-government obstacle data and enterprise digital intensity index to identify the disproportionate compliance burdens on SMEs; finally, we verify the implementation efficiency of institutional tools through the hierarchical mapping of funds, standards and procurement rules and urban cases. The study found that the fixed cost of adapting internal workflows to external regulatory standards constitutes a hidden barrier for SMEs. The contribution of this article is to advance the perspective of institutional Middleware and to demonstrate how the EU can encapsulate compliance complexity into a reusable public infrastructure through policy combination, thereby providing large-scale institutional conditions for a sustainable entrepreneurial ecology.

Keywords: digital single market; European Interoperability Framework (EIF); innovation management; SMEs; sustainable entrepreneurship; Minimum Interoperability Mechanisms (MIMs)

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JEL Classifications: L26; O33; H83; O38

1. Introduction

1.1 Background and Objectives

In this article, the authors use the following terminology. *Compliance and process adaptation* refers to the resources required to adapt internal business workflows to meet external regulatory standards (e.g., implementing specific data governance or e-ID software). *Digital legitimacy* is the institutionally determined ability of digital technologies to be recognised as legitimate, trustworthy, and acceptable through consistent compliance with regulatory, normative, and cognitive expectations. *Improved capacity*: the article refers to the EU's investment in digital infrastructure and the availability of digital public services (e.g., e-government portals and digital identity systems). *Interoperability as a market access condition* - in the context of the EIF, the article defines interoperability not just technically, but multidimensionally. It refers to the ability to interact across borders (between different EU Member States' jurisdictions) and across sectors (between public administration systems and private enterprises' business processes), encompassing legal, organisational, semantic, and

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technical layers. The article discusses interoperability between different national legal jurisdictions (Member States) and between public administration systems and private enterprise workflows. *Lagging adoption* does not refer to optional market tools, but to the mandatory digital procedures required by EU regulations (e.g., the Digital Decade targets, Corporate Sustainability Reporting Directive CSRD, e-invoicing, and public procurement). SMEs are legally required to adopt these digital workflows to interact with public administrations, yet they face significant barriers leading to low uptake or abandonment. *Socio-technical frictions* refer to the operational blockages that occur when technical systems work but legal/organisational processes fail (e.g., a digital form exists, but the e-signature isn't recognised across borders). *Supply and demand divergence* is the gap between the "supply" of government digital services (measured by the Digital Public Service Index) and the "demand/usage" by firms and individuals (measured by Online Interaction rates). *Regressive constraints of friction* here means that the burden falls disproportionately heavier on smaller firms. Compliance costs are "fixed costs" that large firms can amortise, but which act as a high barrier for SMEs.

Over the past two decades, the European Union has promoted the "Digital Single Market" (DSM) through legislative integration and public investment, aiming to build a unified market that can compete with the United States and China. Its policy has long been based on linear logic: as long as digital infrastructure and interoperability improve, service adoption and enterprise innovation will follow. However, macro data reveals the "digital paradox" that improved supply-side capacity coexists with lagging demand-side adoption. This divergence shows that the key to restricting the European digital economy lies not in technological limitations but in socio-technical frictions (STFs). This friction stems from the conflict between legal responsibility and the operation of the technical system within the organisational process, which invisibly increases transaction costs and poses hidden barriers to small and medium-sized enterprises.

Based on this, the article proposes that the digital governance of the European Union is an institutional endeavour aimed at decreasing access barriers. In response to the regressive impacts of compliance on small and medium-sized enterprises (SMEs) during sustainable transformation, the EU is implementing an "Institutional Middleware" architecture. This architecture includes minimum interoperability mechanisms (MIMs), standardised procurement, and targeted funds such as the "Digital Europe Plan," to encapsulate the underlying legal and administrative complexities into a reusable infrastructure and offer a "plug-and-play" compliance environment for green entrepreneurship. This article discusses the Adoption Gap index. As shown in Figure 1, the EU Digital Public Service Index rose steadily (100 to 144.18) from 2017 to 2022, but the "Online Interaction" index fell back to 103.81 in 2022 after a temporary increase driven by the COVID-19 pandemic. This deviation confirms that the crisis-driven forced digitisation has not been transformed into endogenous power, and the interaction mode quickly retreats after the physical restrictions are lifted. The current state of digital services can be characterized as "available but not superior".

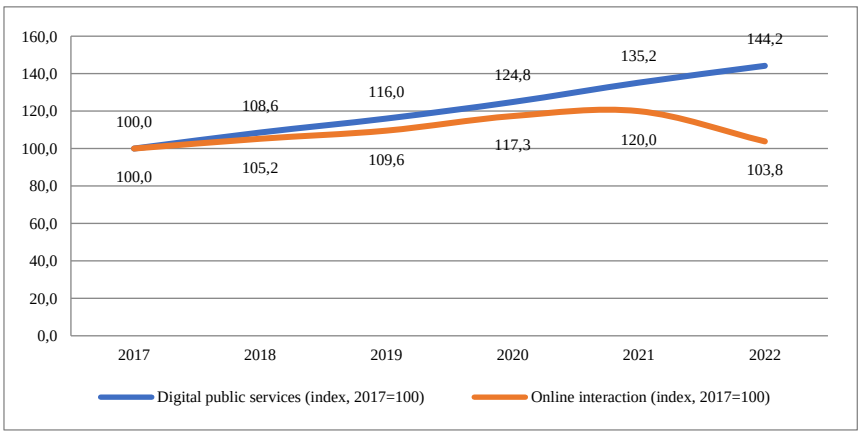


Figure 1. Adoption Gap in Digital Public Services (2017–2022)
Source: Compiled by authors based on Eurostat (2024a) and European Commission (2024a)

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When digitisation fails to reduce process uncertainty and accountability ambiguity, administrative friction can offset technical advantages. For instance, if the complex signing process of transnational electronic tenders cannot achieve deep interoperability, the mere addition of API and computing power is insufficient to bridge the Adoption Gap (European Investment Bank, 2023).

Within the context of the European Green Deal and Corporate Sustainability Reporting Directive (CSRD), this issue becomes especially urgent. The new disclosure requirements impose a fixed cost that is hard for SMEs to bear. Without an affordable, automated compliance solution, environmental standards will burden the most innovative green small- and medium-sized enterprises. Therefore, interoperability is not only a technical feature but also a matter of economic justice, ensuring that SMEs share in the benefits of the green transformation (Godlovitch & Bodin, 2022).

The authors formulate three core research questions (RQs):
RQ1 (Diagnostic): Why has the "rise in supply-side capacity" in the EU digital single market not been transformed into "demand-side adoption"? This article will combine the friction between Figure 1 and EIF levels to explain how legal and organisational blockages lead to an institutional reality of availability rather than superiority.
RQ2 (Distribution Effect): Why does friction become regressive and pose more substantial barriers to SMEs? This article will combine an analysis of funding overlap with how the same set of legal requirements becomes the operating costs of large enterprises, while also examining the survival pressure on SMEs.
RQ3 (Policy Tool): How does the EU encapsulate compliance complexity through Institutional Middleware?

This article will discuss how MIMs, procurement rules and capital flow work together to reduce the cost of cross-domain expansion and cultivate a sustainable entrepreneurship. The contributions of this article are: (1) theoretically reconstructing interoperability as a market access condition for sustainable entrepreneurship; (2) the mechanism puts forward Institutional Middleware to explain the large-scale path under the high legality constraints of the European Union; (3) In practice, it provides policy inspiration on procurement and standard design for transition economies. The subsequent chapters will present the conceptual framework, research design and evidence discussion in turn.

1.2 Literature Review

Contemporary literature increasingly points to the fact that the challenges of digitalisation do not stem from a lack of technology but from issues of legitimacy, power, and institutional embeddedness. At the macro-social level, Staab and Sorg (2025) conceptualise this shift as the emergence of a digital eco-technocracy, where digital and green technologies are used to stabilise society through adaptation but also to generate new legitimacy crises. Their "negative dialectic of technocracy" offers an essential backdrop for analysing the EU: attempts to depoliticise environmental and digital conflicts via techno-administrative solutions heighten legitimacy's reliance on procedures, standards, and expertise. Studies of digital governance also support this shift from political to procedural legitimacy. Ramjit (2025) demonstrates that digitalisation transforms administrative legitimacy by increasing demands for transparency, accountability, and participation, while also exposing risks of reproducing inequalities and power asymmetries. Similarly, Moss (2025) stresses that it is precisely the characteristics of "effective" digital regulation - expertise, flexibility, and adaptability - that widen the gap between regulators and democratic society, turning legitimacy into an issue of justification and explainability rather than mere formal compliance. Together, these studies advance a key thesis: digital legitimacy is an end-to-end institutional process, not merely a byproduct of technological adoption.

At the organisational and entrepreneurial level, the literature consistently demonstrates that legitimacy in the digital context requires proactive, resource-intensive strategies. Research on digital servitisation in manufacturing (Wang & Cui, 2025; Christiansen & Aas, 2024; Christiansen & Aas, 2025) demonstrates that the adoption of digital services is determined not so much by their technical value as by a firm's ability to secure appropriate forms of legitimacy - regulatory, normative, and cognitive - at different stages of development and commercialisation. Crucially, the type of legitimacy required varies over time, making compliance an ongoing process rather than a one-time barrier to entry. A similar logic emerges in research on digital entrepreneurship. Imiren et al. (2024) demonstrate that in contexts with limited institutional resources, entrepreneurs are forced

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to build digital advocacy, curation, and networking capabilities independently to gain legitimacy. Digital legitimacy functions as a fixed cost, disproportionately affecting small and resource-constrained entities. Financial and economic research (Mehmeti et al., 2024) complements this picture. May (2025) and Sonnerfeldt (2025) show that digital transformation can enhance corporate legitimacy through donations, transparency, and improved information quality, but these effects are more pronounced for large or institutionally embedded companies. Jiang et al. (2024) confirm that digitalisation reduces the opportunistic behaviour of controlling shareholders by acting as a mechanism of external oversight and legitimation (Krivins, 2018). Still, its effectiveness depends on the quality of institutions and corporate governance (Durguti et al., 2024). Thus, at the micro level, digital legitimacy acts as a continuous burden rather than an automatic consequence of digitalisation.

A separate strand of literature examines digital platforms as bearers of structural and "extensional" power. Greene and Gilbert (2024) demonstrate that digital platforms shape new institutions through permission systems, necessitating a rethinking of the very nature of legitimacy. Gilbert, Schrage and Behnam (2024) emphasise that "gatekeeper" platforms face, above all, a crisis of moral legitimacy that cannot be resolved by either pure self-regulation or traditional state control. Empirical studies of platforms in developing and transition economies (Chen et al., 2022) show that legitimation strategies depend on the platforms' ability to reallocate resources, assume quasi-public functions, and integrate into regulatory trajectories. This reinforces the asymmetry: large platforms can "internalise" the costs of legitimacy, while SMEs and new entrants remain dependent on fragmented compliance requirements. A growing body of literature links digitalisation to environmental legitimacy. Ai et al. (2025) and Mai (2025) show that digital inclusive finance promotes environmental legitimacy through green investment and innovation, but this effect is uneven across firm sizes and regions. These results confirm that digital instruments can reduce environmental compliance costs, but only when institutional risk-sharing channels are in place. Work on corporate digital responsibility and AI (Yoganathan et al., 2025) demonstrates that clients tend to trust state-institutionalised forms of legitimacy (e.g., compliance with the EU AI Act) rather than pure self-regulation. This highlights the importance of institutional mediation between technology and trust. This finding is echoed by research on e-banking adoption in Latvia (Kaže et al., 2007), which demonstrates that trust in institutional frameworks - rather than innovation alone - was critical for consumer uptake in a knowledge-based economy. Their study reinforces the idea that institutional mediation plays a decisive role in enabling technological legitimacy, particularly when information asymmetries or cultural resistance exist.

While current research focuses heavily on system-level legitimacy and firm strategies, several studies stress the need to examine the human and behavioural dimensions underpinning digital adoption. In particular, Kaže et al. (2022) present an innovative image-based methodology for understanding individual value orientations that drive decision-making in digital and sustainability contexts. Their work shows how personal value systems, such as openness to change or preference for tradition, can influence the willingness to engage with digital tools, particularly in uncertain regulatory environments. This value-based insight is especially relevant in designing inclusive digital ecosystems that respect cultural and motivational diversity.

Empirical research further links social values to systemic behaviours, including informal economies and regulatory avoidance. A study of population participation in the grey economy demonstrates that value orientation strongly predicts whether individuals perceive state regulations as legitimate and thus choose to comply or evade them. These findings suggest that building legitimacy at scale must go beyond formal compliance and actively address the socio-cultural perceptions of rules, which are critical to the EU's digital legitimacy strategy.

In the same context, the enabling role of digital environments in fostering sustainable entrepreneurship (Sceulovs et al., 2011; Sobczak, 2025; Varzaru, 2024). They argue that e-environment tools not only increase transactional efficiency but also promote value alignment between digital initiatives and broader sustainability goals, especially when implemented in small-scale economies. Similarly, the importance of coordinated spatial governance, where digital innovation is interlinked with community-level sustainability goals, is emphasised in the research (Miszczak et al., 2024). It highlights that governance efficiency and perceived legitimacy are

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interdependent: digital systems must not only work but also be accepted and trusted within local socio-political ecosystems.

Despite the wealth of empirical research, the literature primarily analyses the legitimation strategies of individual actors (firms, platforms, entrepreneurs) or critiques technocratic legitimation regimes at the macro level. Work on transdisciplinary implementation support (Carey et al., 2024) only hints at a shift toward tools that enable collective deliberation and structuring of technological legitimacy, but does not offer scalable institutional solutions. In this context, the question of how the costs of digital and environmental legitimacy can be institutionally aggregated, standardised, and reused, particularly for the benefit of SMEs, remains underdeveloped.

Against this background, this study proposes considering institutional Middleware (MIM) as the missing layer of analysis between macro-debates about digital technocracy and legitimacy and firms' micro-strategies for ensuring compliance. Unlike existing work, which focuses on actors (Duarte & Carvalho, 2024; Calzati & van Loenen, 2025), this article shows how the EU, through standards, procurement (Krivins & Vilks, 2013), and financial instruments, transforms ongoing legitimacy costs into collective, reusable institutional pathways. This allows us to rethink the "double transition" – not as the sum of digitalisation and greening, but as an opportunity to design interoperable, auditable, and scalable compliance structures.

1.3 Research Objectives and Framework

To understand why technology supply has not automatically translated into adoption, it is not sufficient to rely solely on technology acceptance models (such as TAM). This article adopts a Socio-Technical Systems perspective to examine e-government and UDT infrastructure as a composite system comprising legal norms, organisational processes, semantic definitions, and technical interfaces. From this viewpoint, the technical capability of "available" does not necessarily align with the institutional arrangement of "diffusible," and the adoption gap often stems from a disconnect across system levels. The European Interoperability Framework (EIF) offers a fundamental model for analysing this disconnection, and this article further proposes Institutional Middleware as an interpretive mechanism to clarify how the European Union alleviates hierarchical friction through a combination of policy tools, transforming compliance complexity into a reusable market infrastructure.

Since its initial proposal in 2004, EIF has become the foundation for coordinating EU digital public services (European Commission, 2004). EIF breaks down interoperability into four interdependent levels: Legal, Organisational, Semantic, and Technical. Any imbalance at any level can hamper the end-to-end process and cause "interoperability friction" (European Commission, 2017b; Campmas et al., 2022). Among these, legal interoperability has the most rigid "hard constraint" nature: even within the framework of the General Data Protection Regulation (GDPR), if the legal effect of electronic identity or signatures cannot be recognised across domains, the legality of the transaction will be immediately contested (European Commission, n.d.-a). Organisational interoperability focuses on aligning business processes. Variations in approval sequences and responsibility attribution across jurisdictions force enterprises to develop multiple compliance strategies, significantly increasing hidden costs (European Commission, 2017a). Semantic interoperability requires a shared understanding of data. In green governance, if definitions like "carbon footprint" lack standardised criteria, enterprises must resort to costly manual processes to replace automated compliance (European Commission, n.d.-a). Conversely, while technological interoperability has progressed with the widespread adoption of open standards, evidence indicates that a single technological enhancement cannot replace the need for aligned, overarching systems, prompting member countries to continue promoting national frameworks to bridge the remaining gaps (Kalogirou et al., 2022).

Based on this, this paper proposes Institutional Middleware as a theoretical extension of EIF in governance practice. Middleware is often referred to as "software glue" in computer science. Its function is to shield the underlying complexity between the operating system and the application, and to provide unified authentication, messaging, data access, and other general services (Tanenbaum & van Steen, 2017). By analogy, the EU's diversified legal and administrative system constitutes the underlying "operating system", while the large-scale deployment of SMEs' transnational business and green solutions is like an "application".

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In the absence of Middleware, entrepreneurs must bear the adaptation cost of system fragmentation alone. Institutional Middleware is not a single technical solution but a combination of policies and institutional arrangements. It aims to encapsulate the compliance complexity under strict legal constraints into reusable modules, thereby reducing social and technological frictions and improving the feasibility of cross-domain expansion. Specifically, it comprises three complementary components: the minimum interoperability mechanism (MIMs) as a "standard interface", providing a general specification for cross-city systems (Open & Agile Smart Cities, 2025); a coordinated procurement rule for "agreement", which prevents locking and lowers the entry barrier by embedding interoperability clauses (UN-Habitat, 2023); and a strategic fund for "fuel", offering subsidies for system migration through DEP and NGEU (European Commission, 2022). Therefore, the theoretical framework of this article redefines "interoperability" from a purely technical issue into a market entry prerequisite, emphasising that the key to digital transformation in the European Union is not merely to enhance technical capabilities, but to unlock growth potential for a sustainable entrepreneurial ecosystem by publicising, modularising, and scaling up compliance costs.

2. Methods

This article adopts an explanatory research design using multi-source evidence. It builds an evidence chain that includes diagnosing the macro-adoption gap, identifying micro-friction mechanisms, hierarchical mapping of policy tools, and application verification in urban cases, systematically answering RQ1-RQ3. The core judgement of the study is that the adoption of EU digital governance is not mainly due to insufficient technology supply but is closely related to STFs at the legal and organisational levels of EIF and its regressive burden on SMEs, and can be partially encapsulated and publicised through the tool combination of Institutional Middleware.

For RQ1 (diagnosis), this article first builds a time series index to depict the deviation between supply and adoption. We use the digital public service dimension in the European Commission's European Innovation Scoreboard 2024 to represent the supply side, and we extract Eurostat's statistical data on online interactions between individuals and public institutions to represent the demand side. To ensure vertical comparability, this study indexed the data on both sides ($Index_t = \frac{Value_t}{Value_{2017}} \times 100$) based on 2017. The two curves presented after visualisation intuitively established the empirical starting point of subsequent friction diagnosis.

To further identify the friction mechanism in RQ1 and analyse the distribution effect in RQ2, this paper integrates two types of complementary micro-evidence. First, Eurostat's "e-government barrier" dataset reveals the block structure of online interaction: statistical results show that, compared with pure technical failures, legal frictions such as identification and electronic signatures carry significant weight. To better understand the consequences of process fracture from an enterprise perspective, we introduced the eGovernment MONITOR 2024, released by the German Initiative D21. The microdata in the report characterises this barrier as *Medienbruch* (media discontinuity) and *Haftungsangst* (liability anxiety), and explain how risk-avoidance psychology leads users to retreat from digital channels to offline alternatives. In the enterprise heterogeneity analysis of RQ2, the research focuses on verifying the regressive nature of compliance costs. Through the measurement and analysis of Eurostat's "Digital Strength Index", SMEs and large enterprises show significant hierarchical differences in their digital capabilities. It is worth noting that the supplementary investigation evidence from the European Investment Bank (EIBIS 2025) excludes the competitive explanation of "infrastructure shortage" and clarifies that the current constraint bottleneck has been significantly transferred from the physical access layer to the application adaptation layer, thus confirming the asymmetric constraints of institutional friction on small and medium-sized enterprises.

For RQ3 (policy tools), this article breaks down the operation of institutional Middleware into three elements: capital, standards, and procurement rules. Based on the EU "large-scale pilot plan" budget document, we have rebuilt the middleware capital investment structure. At the same time, in combination with the NGEU/RRP data set from the Bruegel Research Institute, tagging analysis further highlights the overlap between digital investment and green and social goals. It verifies the guiding role of funding tools in shaping sustainable

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application scenarios. In terms of standards and rules, this article maps design fragments, such as eIDAS (Electronic Identification, Authentication, and Trust Services) and GDPR, procurement interoperability terms, and intelligent data models, to the legal, organisational, semantic, and technical levels of the EIF according to the preset codebook.

Finally, this article selects Barcelona and Bologna as case studies for mechanism verification. The former exemplifies the middleware application mode driven by "procurement rules and data ownership clauses," and the latter illustrates the process remodelling mode driven by "participation process institutionalisation and LDT sandbox." Both cases are supported by official documents, project reports, and practical materials to demonstrate the real effectiveness of cross-level mechanisms in urban governance.

3. Results

3.1. Result A: The cost of legitimacy and the friction between social technology

In the highly regulated market environment of the European Union, the main obstacle to digital adoption is not primarily the lack of system availability, but rather the establishment and recognition of legitimacy in the digital space across different domains. The trust system in the physical world relies on paper documents, seals, face-to-face identity verification, and stable written norms. These mechanisms define clear boundaries for evidence, effectiveness, and responsibility in long-term institutional practice. Once in the digital environment, legitimacy is embedded in end-to-end processes such as identity verification, electronic signatures, data compliance, and audit trails, which are based on identity and signature validity under the framework of eIDAS, as well as the legitimacy and traceability of data processing under GDPR (Sharif et al., 2022). Consequently, legitimacy is no longer just a background condition but becomes a prerequisite for establishing transactions and initiating a series of standard operational processes. These frictions are mainly located within the legal and organisational layers of the EIF. They are exacerbated in high-frequency B2G and B2B2G interactions, especially during bidding, licensing, subsidy applications, and CSRD-mandated ESG reporting. This scenario is not simply a matter of "citizen experience'. Still, it serves as a critical channel for entrepreneurial subjects to access the market, because the failure of identity and signature verification can directly prevent transactions from being established, thus creating barriers rather than minor inconveniences. Eurostat statistics on the problems encountered by Internet users when interacting with public authorities provide a direct observation of the pattern of friction (see Figure 2).

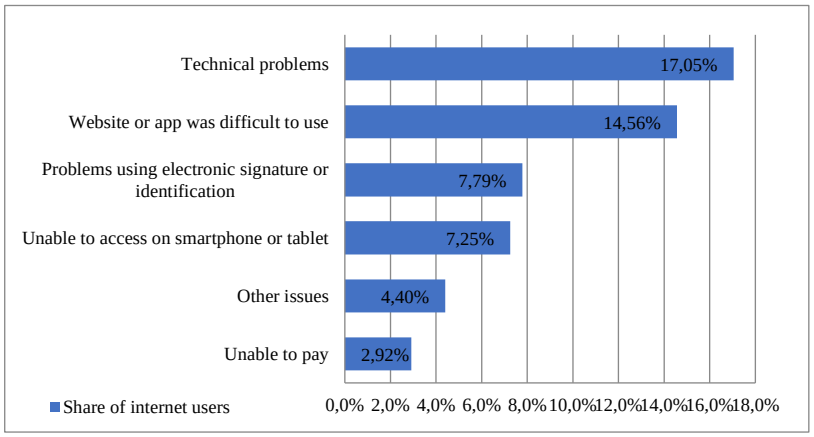


Figure 2. Types of Socio-Technical Frictions in E-Government Interactions.
Source: Eurostat (2024b).

In terms of proportion, "technical problems" account for the highest share (17.05%), making it easy to attribute adoption obstructions to system congestion or website failures. However, what is more explanatory is the type of friction associated with the nature of "hard constraint." Although the "electronic signature or identification problem," accounting for 7.79%, is not the highest, it addresses the core institutional conditions for digital transactions. In B2G scenarios, website failures usually result in delays, and enterprises may still submit

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materials after the system is restored; however, failures in identity authentication or signature mean the system cannot recognise the subject's qualifications, preventing the submission of tenders, the application for licences, and the validation of contracts. This mechanism can be summarised as a chain of failures from "identity and signature failure" to "transaction non-establishment," resulting in market access failure due to the transaction being legally invalid, not merely a loss of efficiency. Consequently, this type of friction highlights a bottleneck in the EIF Legal Layer, rooted in the institutional inconsistency of recognising effectiveness and traceability of responsibility. It cannot be easily resolved through UI optimisation or server upgrades (Sharif et al., 2022). Simultaneously, when the legal layer's bottleneck and organisational layer's process are not aligned or superimposed, even if the service is technically "available," it is unlikely to be regarded as "better" by market participants. This results in a return to offline methods and a diminished trust in digital channels.

Germany's micro-evidence further shows how legal and organisational frictions can be turned into risk perception and abandonment behaviour (Figure 3).

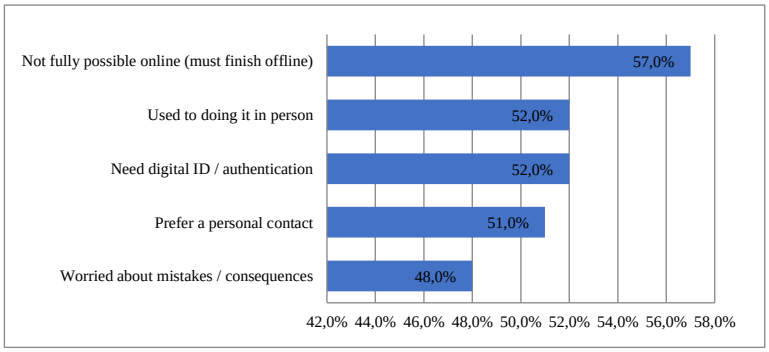


Figure 3. Reasons for Abandoning E-Government Services in Germany
Source: Initiative D21 (2024).

The survey shows that 57% of users give up because the process cannot be completed entirely online, indicating a gap in Organisational Interoperability, that is, *Medienbruch*. When the end-to-end process is split into online and offline sections, users need to understand two sets of rules and material requirements simultaneously. Digitalisation not only reduces transaction costs but also increases coordination costs and uncertainties. More importantly, 48% of users said that they were “afraid of making mistakes or facing consequences”, which can be summarised as *Haftungsangst*. In Germany's legalised environment, *Schriftformerfordernis* (written-form requirement) has long been regarded as the cornerstone of legal certainty. The digital process is more likely to raise uncertainty about the validity of the signature, the integrity of the evidence, and the path to relief. Small and medium-sized enterprise owners are worried about the irreversible consequences of an incorrect submission or about the lack of the same psychological certainty in electronic materials in dispute scenarios. Given that software is within the scope of the EU Product Liability Directive, this uncertainty may also spill over into adoption decisions for digital products and services (Weiss, 2025). Therefore, *Haftungsangst* is not an individual preference but a rational response to the uncertainty surrounding legal effectiveness and organisational process fractures. It explains why "passive digitisation in crisis times" is challenging to transform into normal adoption.

The above friction does not affect enterprises of different sizes equally. The main reason is the fixed cost nature of compliance expenses. Establish a data governance and audit system that complies with GDPR, purchase and integrate qualified eIDAS-related services, and understand and implement cross-border procurement and authorisation rules, all of which require ongoing investment. Large enterprises can spread fixed costs and achieve reuse through specialised legal, compliance, and IT teams. In contrast, for small and medium-sized enterprises (SMEs) with limited resources, these exact requirements are more likely to act as market-entry barriers. The digital intensity index further highlights the difference between enterprises.

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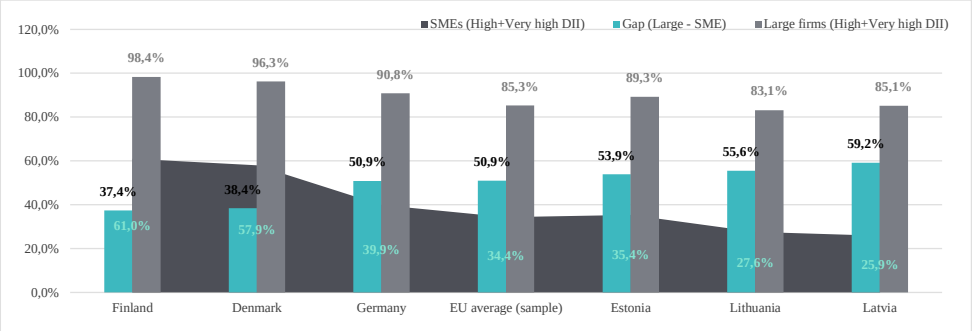


Figure 4. Digital Capability Gap: SMEs vs. Large Enterprises
Source: Eurostat (2023)

Figure 4 above shows that in the Baltic countries (Latvia, Lithuania, Estonia), the digital strength gap between SMEs and large enterprises exceeds 50 percentage points, and in Latvia, it is close to 60%. This "Baltic paradox" suggests that advanced infrastructure does not automatically lead to the diffusion of small and medium-sized enterprises, and that institutional friction and ability constraints are often centralised at the application level. It is more reasonable to understand that a single factor does not drive this gap, but instead that it results from a combination of structural, policy, and ability constraints. On the one hand, cross-domain digital investment offers economies of scale, and digital intensity is easier to accumulate and to turn into a reusable process in large enterprises. On the other hand, digital public investment initially falls at the government systems and infrastructure level, while adoption incentives and compliance adaptation lag on the SME side. At the same time, financing, human capital, and management capacity constraints make it more difficult for SMEs to convert compliance fixed costs into dilutable operating costs, ultimately widening the capacity gap. The three jointly point to the same conclusion: compliance friction has an obvious regressive nature, objectively raising the entry threshold, making it easier for existing large enterprises to expand across domains while hindering green small and medium-sized enterprises from entering the market on a larger scale. When innovators of sustainable solutions cannot bear the cost of cross-border compliance and process adaptation, the diffusion of green innovation will be limited, and the EU's green transformation goals will be indirectly constrained (Demirer et al., 2024). In summary, the result A confirms that the institutional root cause of the Adoption Gap focuses on the legal and organisational friction generated by legality, and inhibits the integration of SMEs into digital ecology in a regressive way, which provides an empirical starting point for the next section on how to encapsulate complexity and reduce friction in Institutional Middleware.

3.2 Result B: Middleware as a large-scale tool, the EU's institutional response

In light of the regressive nature of STFs and the compliance costs revealed by Result A, the European Union has adopted an active market-building strategy: to encapsulate compliance and adaptation risks in a fragmented environment by deploying Institutional Middleware. In the absence of this Middleware, entrepreneurs must bear the hidden costs of cross-domain expansion alone, including interpreting off-site rules, accessing identity systems, manually translating data semantics and adapting proprietary interfaces. Institutional Middleware aims to transform these decentralised fixed costs into reusable, auditable public infrastructure, so that scale no longer relies on the compliance capabilities of individual enterprises but on the "reproducible path of the market".
Empirical evidence shows that this strategy is promoted collaboratively through financial support and standard formulation, and it jointly emphasises "scalability" and "replicability".

First, the funding tool aims to subsidise interoperability migration, lowering the threshold for system conversion and mitigating risks. Figure 5 shows that the Digital Europe Plan (DEP) emphasises deployment and diffusion more than Horizon Europe. Its budget directly subsidises the construction of Institutional Middleware (European Commission, 2022), thereby transforming the costs of compliant learning and trial-and-error into public investment.

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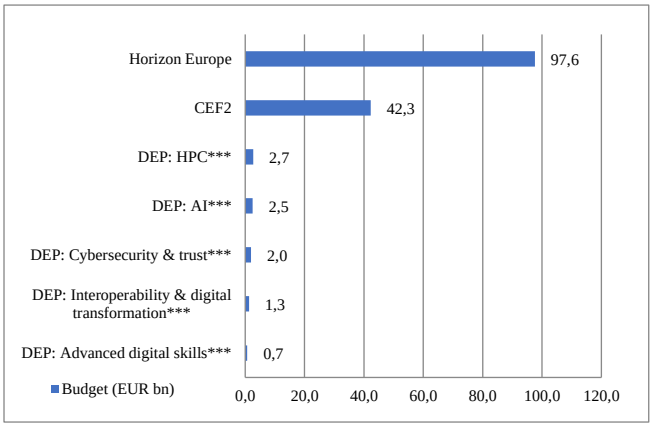


Figure 5. EU Funding Schemes as Institutional Middleware
Source: European Commission (2019).

For example, the European Digital Innovation Hubs (EDIHs) provide a "test before invest" environment, allowing SMEs to verify the scheme's compliance at low risk, thereby reducing the uncertainty premium caused by *Haftungsangst* (Vijayakumar & Davidova, 2025). At the same time, the NGEU Recovery Fund gradually bundles digital investment with green transformation goals to promote the formation of a "sustainable digital" demand-side market.

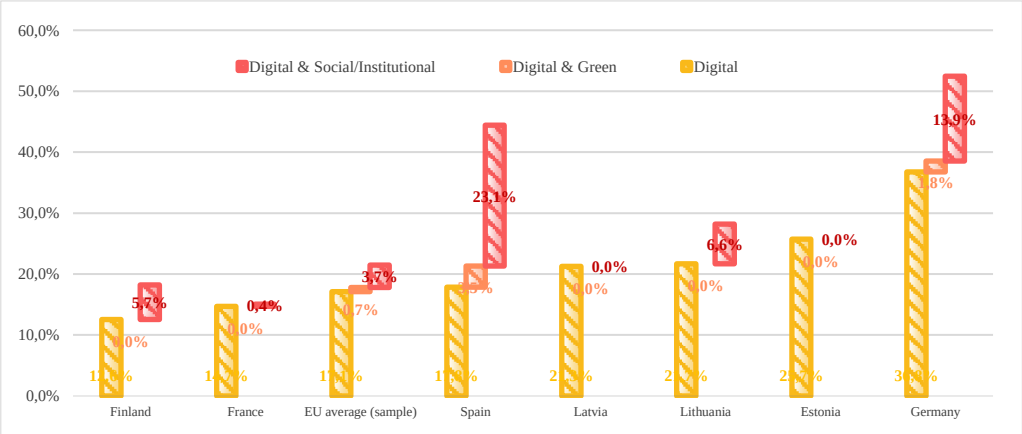


Figure 6. Overlap Between Digital, Green, and Social Funding in NGEU
Source: Bruegel (2023)

Figure 6 above shows that Spain, Germany and other countries invest funds in areas of digital and green overlap, such as digital monitoring and governance of energy efficiency, which means that Middleware not only reduces barriers to entry but also fosters the environment for scalable application scenarios and sustainable business models through fund allocation (European Commission, 2024b). In contrast, the Baltic countries show no overlap under the criteria for this label, which is more likely to reflect differences in policy design, classification criteria, or priority preferences rather than a lack of digital capacity. It suggests that transition economies still need to translate capital tools more clearly into support for the adoption and supply of reusable compliance paths for green entrepreneurship.

Secondly, the minimum interoperability mechanisms (MIMs) constitute the standard kernel of Institutional Middleware, which is promoted through networks such as OASC and "Living-in.EU" to curb fragmentation and supplier lock-in (Open & Agile Smart Cities, 2025). MIM1 (context information management, OMA NGSI-LD) reduces the cost of cross-city technology adaptation with a general API and context link mechanism, bringing the application closer to the expansion conditions of "one-time development, multi-place deployment"

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(Bauer, 2022); MIM2 (shared data model) reduces "translation friction" through unified semantics and field structure, providing prerequisites for green data processing and compliance reporting automation; MIM3 (ecosystem transaction management) solidifies the credible boundaries of data sharing and service exchange through permissions, records and audit mechanisms, and responds to the core requirements for traceability in a high legitimacy environment (European Commission, n.d.-b). Funds and MIMs encapsulate "migration cost and risk exposure" and "adaptability complexity and semantic fragmentation," respectively, transforming interoperability from rhetoric into reusable infrastructure and laying the institutional foundation for the next section on procurement rules and urban cases on how to open up SME market opportunities further.

3.3 Result C: From interface to process, implementation at the urban level

Institutional Middleware is not only highlighted in Brussels' policy document; it is also being tested under real-world stress in urban laboratories across Europe. Barcelona and Bologna examine two complementary approaches. The former incorporates open standards and data ownership into procurement contracts. It shifts the competition structure to the market-access side. At the same time, the latter includes participation programmes and the Local Digital Twin (LDT) in the policy testing process to reduce uncertainty around innovation, trial, and error. Together, these cases show that only when Middleware is embedded into actual transactions and decision-making processes can it substantially reduce STFs and transform "compliance" from a burden into a vital condition for sustainable entrepreneurship.

In Barcelona, "Technological Sovereignty" was made a strict requirement within the procurement system, effectively incorporating the "agreement layer" of Middleware into the contracts and market access regulations (Calzada, 2019). The city council adopted open standards and, whenever possible, mandated the use of open-source software in bidding processes, emphasising that data generated by public services is a public asset owned by the city and its citizens rather than by suppliers (Ajuntament de Barcelona, 2018). The main aim of this approach is not merely to express a position but to reduce the structural advantage of supplier lock-in, thereby enabling smaller local enterprises to offer modular services around open interfaces. This lowers the proprietary adaptation costs needed to access the public market, facilitating the development and delivery of solutions such as energy savings, waste reduction, and green logistics (Ajuntament de Barcelona, 2018). Based on this, a testable hypothesis can be proposed: when urban procurement rules mandate open standards and interoperability, the costs associated with supplier lock-in decrease, entry barriers are lowered, and the participation and innovation potential of SMEs are more likely to increase (P1).

Bologna focuses on organisational interoperability and process reshaping. Its "Civic Imagination Office" enables citizen collaboration to obtain enforceable legal form by standardising participation procedures and promoting the signing of the "Patti di collaborazione", thereby transforming "participation" from loose opinions into structured input that can enter the governance process (Fondazione Innovazione Urbana, 2023). At the same time, LDT is positioned as a testing ground for policy and innovation. It not only carries 3D models, but also connects the simulation and evaluation of social and environmental variables, so that start-ups can test the impact of transportation, energy and other solutions on emissions and urban operation in a controlled environment, reduce the cost and responsibility exposure of trial and error in the real world, and then form a green innovation safe harbour closer to "scalable" (Comune di Bologna, 2023). This also supports a proposition: when cities provide digital twins or sandboxes as test environments, the risk of innovation failure is partially externalised, and the trial rate and iteration speed of green solutions are more likely to increase (P2). Further, when public data is clearly defined as a public product and can be called in compliance under the rules, it is easier to form a commercial closed loop of "data-model-service" to provide continuous impetus for the diffusion of green innovation (P3).

Overall, the experience at the city level shows that the key to Middleware is not the number of interfaces, but whether the procurement rules and collaboration processes can "encapsulate" compliance complexity into reusable infrastructure and redistribute market opportunities from a few large suppliers to a broader range of SMEs and sustainable entrepreneurs.

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4. Discussion

Comprehensive analysis demonstrates that interoperability in the European Union has transcended technical dimensions to become a core economic enabling mechanism. The persistence of the aforementioned Adoption Gap stems from the fact that SMEs, often lacking administrative resources, face excessive transaction costs. Institutional Middleware aims to flatten this cost curve.

4.1 Insights from Transitional Economies: The Baltic Paradox

The Baltic Paradox provides a very explanatory contrast situation. The three Baltic countries have overall outstanding performance in the usability of digital public services, and their electronic identity and government portal systems are relatively mature. Accordingly, the proportion of enterprises that regard "insufficient digital infrastructure" as the primary investment obstacle is also low (European Investment Bank, 2023; European Investment Bank, 2025). But at the same time, the gap in digital strength between SMEs and large enterprises in these countries remains evident, particularly in Europe (Eurostat, 2023). This is the core of the "paradox": high-capacity and low-infrastructure barriers have not naturally led to broad digital deepening among SMEs. Figure 7 more directly reflects enterprises' feelings about the constraints imposed by "infrastructure availability".

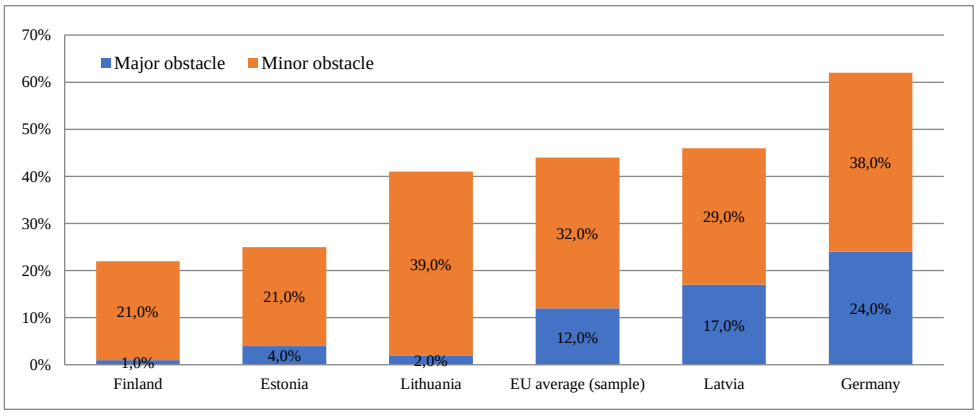


Figure 7. Digital Infrastructure as an Investment Barrier
Source: European Investment Bank (2025)

It can support the judgement that "the obstacles at the technical and infrastructure level are not prominent", but it cannot infer that the legal, organisational or semantic layers STFs are also low. Therefore, a more secure interpretation is that when infrastructure is no longer the most significant source of constraints on the enterprise side, the bottleneck limiting the further digitisation of SMEs is often more likely to focus on the ability formation process of the application layer and the organisational layer, such as end-to-end process integration, cross-domain compliance adaptation, and the continuous investment required to embed advanced digital workflows in daily operations.

To avoid a single causal explanation, this article views this paradox as the result of the superposition of multiple mechanisms. First, cross-domain digital investment naturally yields economies of scale and reuse. Data governance, process reengineering, and advanced analytical capabilities are more likely to accumulate and form replicable capabilities within large enterprises, making digital intensity more concentrated there. Secondly, even if digital investment in the public sector significantly improves overall capacity, it often prioritises the government system and infrastructure. If the adoption incentives for SMEs, compliance adaptation support, and the supply of reusable tools are relatively lagging, the notion that "the supply side becomes stronger" will not automatically lead to "SME side diffusion". At the same time, constraints related to financing, human capital, and management capacity will affect whether enterprises can convert the fixed costs of GDPR, eIDAS, and cross-domain process adaptation into manageable operating costs, thereby influencing SMEs' ability to invest in advanced applications such as AI and big data analysis. These mechanisms are not mutually exclusive, nor do they require strict prioritisation within the evidence scope of this article. Still, they collectively highlight a clear policy implication: for transition economies, the focus of institutional Middleware should shift from

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merely expanding infrastructure to supporting adoption and capacity building for SMEs, such as standard compatibility advice, compliance service provision, and tool arrangements for migrating fixed costs in the sharing system, to prevent the diffusion of capabilities that are structurally blocked by enterprise scale (Ruža et al., 2024).

4.2 Governance as a Platform

A full-text analysis reveals that the EU interoperability agenda is shifting from technological enhancements to market-oriented institutional development. The ongoing adoption gap indicates that merely improving supply-side capacity does not automatically normalise demand-side adoption. This is because STFs reinforce legality requirements and process complexities, which translate into transaction costs and impose stricter, regressive constraints on SMEs. From this perspective, Institutional Middleware is a platform-based governance architecture: it aims to shift the burden of compliance and adaptation needed for cross-domain expansion from individual enterprises to reusable institutional pathways and public capabilities. This way, scale is no longer dependent on entrepreneurs repeatedly "manually solving compliance problems", but instead relies on an executable, auditable, and replicable institutional infrastructure.

In this platform-based landscape, standards, procurement rules, and capital networks function as "arrangements". Standard mechanisms (such as MIMs) encourage cross-domain adaptation, shifting from project-based customisation to reusable pathways, which reduces the marginal cost of semantic conversion and technology integration; procurement and data ownership clauses formalise open standards, hinder the feasibility of suppliers locking in and expanding SMEs to access the public market; capital and capacity networks support early migration costs and uncertainties through subsidies, experimental environments, and coaching mechanisms to share systems, fostering compatibility and capacity diffusion. The urban case further illustrates that this kind of platformisation does not happen automatically. Only when the institutional Middleware is genuinely embedded in the transaction and decision-making process can it significantly reduce friction and open the window of opportunities for sustainable entrepreneurship. For the entrepreneurial ecology, its importance is not to guarantee the "necessary success" of expansion, but to minimise the uncertainty of cross-city entry and compliance adaptation, making innovation costs more likely to shift from repeated compliance to product iteration, thereby providing more stable institutional conditions for scaling and replicating green solutions.

Conclusions

The research evidence in this study shows that the core bottleneck of the long-term "high availability, low adoption" dilemma in the EU Digital Single Market is not a lack of platforms or infrastructure, but rather structural Socio-Technical Frictions (STFs) caused by digital legitimacy requirements. In practice, this bottleneck manifests as legal requirements that must be enacted through end-to-end digital procedures (such as eIDAS-based identification and signatures, GDPR-compliant data processing, and auditable process tracking). These requirements generate frictions at the legal and organisational layers, which translate into fixed "legitimacy costs". Due to the high upfront investment and weak correlation with enterprise scale, these costs have a regressive effect: large firms can amortise them through specialised legal, compliance, and IT capabilities, whereas SMEs face them as a de facto market entry threshold. This also explains the adoption gap we have observed, where the demand-side penetration rate lags even with improved supply-side conditions, and underscores the importance of this restriction for sustainable small and medium-sized enterprises operating in a high-compliance environment.

Based on this diagnosis, the paper develops "Institutional Middleware" as an interpretive framework to explain how the EU attempts to transform fragmented compliance burdens into reusable public infrastructure. We do not treat "Institutional Middleware" as a fully estimated causal model, but instead offer a mechanism-oriented explanation supported by multiple sources of evidence and case illustrations, thereby clearly separating empirical support from explanatory content. Our analysis uncovers a pattern consistent with a mechanism across EU policy instruments and urban cases: (1) recurring legal and organisational frictions are apparent in user-reported barriers and abandonment behaviours; (2) these frictions create fixed costs with regressive effects on SME capabilities; and (3) EU policy instruments are increasingly employed as a coordinated chain of tools aimed at externalising part of the compliance burden.

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Under this framework, we identify three complementary mechanisms. First, standards - specifically Minimum Interoperability Mechanisms (MIMs) - encapsulate semantic and technical complexity through reusable interfaces and shared specifications, thereby reducing integration costs and limiting vendor lock-in. Second, procurement operationalises openness by embedding interoperability and data governance requirements into market access rules; the Barcelona case illustrates how procurement clauses can lower entry barriers for small suppliers by making standards enforceable in actual transactions. Third, capital through funding instruments such as the Digital Europe Programme (DEP) and NextGenerationEU plays an enabling role. By subsidising early migration costs and supporting experimentation, it de-risks the adoption of new standards and mitigates the obstacle of fixed compliance costs for SMEs. Together, these elements reflect the EU's attempt to treat compliance as infrastructure.

Crucially, the sustainability dimension is not an add-on but a primary application domain, as legitimacy costs in this field have significant economic consequences. Under the EU's "Twin Transition" strategy, green entrepreneurship increasingly depends on the ability to meet requirements under the Corporate Sustainability Reporting Directive (CSRD) and other regulations through interoperable, auditable digital workflows. Institutional Middleware provides a practical design logic: translating sustainability reporting and monitoring requirements into interoperable data structures and auditable process modules. This allows compliance to become embedded, reusable, and closer to automation, ultimately reducing rather than amplifying entry barriers for green SMEs.

Finally, the transition process remains inconsistent. Germany's Haftungsangst (liability anxiety) shows that technical Middleware must be paired with legal clarity on liability boundaries. At the same time, the "Baltic Paradox" indicates that infrastructure alone cannot close the capacity gap without supporting capacity-building measures. Therefore, policy success should be assessed not only by service availability but also by the structural support provided to entrepreneurs driving the green transition. Future research can examine this framework more directly by measuring whether specific middleware deployments (e.g., procurement interoperability clauses or MIM-based implementations) decrease abandonment rates, reduce compliance costs, and increase SME participation in digital and green markets over time.

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INTEGRATED MODEL FOR IMPROVED LOGISTICS WITH A FOCUS ON FORWARDING AND WAREHOUSING SERVICES

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Abstract. The growing complexity of global supply chains and the increasing integration of regional economies have elevated the role of logistics as a critical link between production and consumption. Forwarding and warehousing services, as core components of logistics operations, face continuous challenges related to operational efficiency, service quality, and coordination. This study aims to develop an integrated model to enhance the performance and interconnectivity of forwarding and warehousing services. The research is based on a multi-stage methodology, combining theoretical analysis of logistics integration, identification of critical operational factors, and the construction of a systemic model framework. Key tasks include examining interdependencies between forwarding and warehousing, analysing operational challenges, and designing a model that optimises service quality, cost efficiency, and reliability. The resulting integrated model provides a structured approach to improving logistics service coordination and offers practical recommendations for implementation in real-world supply chain environments. This study contributes to both logistics theory and practice by offering a comprehensive framework for forward-looking management of forwarding and warehousing services, supporting more resilient and efficient supply chains.

Keywords: forwarding; warehousing; supply chain; risk management

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JEL Classifications: M10, O32, R40

1. Introduction

The rapid advancement of economic globalisation and the strengthening of regional integration have significantly increased the importance of logistics as a vital link between production and consumption. As noted by Thui & Son (2024), the logistics sector has become a foundational component of global trade flows, ensuring that goods move efficiently across borders and markets. In this dynamic environment, forwarding and warehousing service providers face unprecedented challenges, as evolving customer expectations, technological transformation, and market uncertainties reshape the competitive landscape (Katinienė, Jezerskė & Vaičiūtė, 2021; Ndlovu, Nkondo & Manchidi, 2025).

Previous research examining the interdependence between logistics performance and economic development highlights that the logistics industry acts not only as a facilitator of supply chain operations but also as a key driver of both global economic integration and regional economic growth (Wang et al., 2021; Tubis & Grzybowska, 2022). Consequently, the effective functioning of forwarding and warehousing services plays a substantial role in the broader economic system, influencing business continuity, production stability, and national competitiveness (Naz & Ejaz, 2023; Arabelen & Kaya, 2021; Tubis, & Grzybowska, 2022).

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Integrated management of forwarding and warehousing services has therefore become increasingly essential. As Struk & Karpii (2019) emphasise, the coordination of these activities is critical to ensuring seamless supply chain operations – from the early stages of production to final consumption. Issues related to product delivery, transportation, and forwarding, particularly during contract execution, remain highly relevant in both theory and practice. Such challenges can affect not only the efficiency of logistics processes but also the economic activity of entire countries, as pointed out by Sujatmiko et al. (2024).

The primary objective of this study is to develop an integrated model that enhances the effectiveness, coordination, and overall performance of forwarding and warehousing services. The model aims to identify key operational factors, reveal interdependencies between service components, and propose a structured framework to improve *service quality*, *cost efficiency*, and *operational reliability* within logistics systems. To achieve this objective, the research focuses on the following specific tasks:

1. Analyse the theoretical foundations of forwarding and warehousing services, including their roles within modern supply chains and their impact on economic development.
2. Identify key factors and challenges affecting the integration and performance of forwarding and warehousing operations.
3. Examine interdependencies between forwarding and warehousing services to understand how operational decisions in one domain affect the other.
4. Develop a conceptual integrated model that coordinates forwarding and warehousing activities to optimise service quality, cost efficiency, and operational reliability.
5. Provide practical recommendations for the implementation of the integrated model in real-world logistics systems to improve service effectiveness and supply chain performance.

To achieve the objective and fulfil the tasks, the research employs a multi-stage methodological approach. First, a theoretical analysis is conducted to synthesise existing scientific insights on logistics integration, forwarding processes, and warehousing management. This theoretical foundation enables the identification of core dimensions and critical factors relevant to the integration of forwarding and warehousing services. Subsequently, a comparative analysis and systemic modelling approach are applied to design the integrated model. The methodology includes structural interpretation of relationships among service elements, evaluation of functional compatibility, and formulation of model components based on established logistics management principles. The final stage involves conceptual model construction, ensuring that the resulting framework is coherent, practitioner-oriented, and suitable for application in real-world logistics environments.

2. The Essence and Specifics of Forwarding Services

The term "transport" is usually associated with companies that own a fleet of vehicles used for cargo transportation. In contrast, "forwarding" includes not only the organisation of cargo transportation but also additional services such as cargo escort, customs procedure handling, warehousing, and other logistics services (Skiba & Karas, 2022). Unlike direct cargo transportation, forwarding services focus on the intermediary function between cargo owners and carriers, ensuring all additional logistics stages such as warehousing, customs procedures, and cargo monitoring (Grebennikov et al., 2024). One of the most significant issues is that companies providing forwarding services operate under different terms and principles (Naz & Ejaz, 2023; Arabelen & Kaya, 2021; Tubis & Grzybowska, 2022).

Key functions of a freight forwarder include (Skiba & Karas, 2022):

- *Organising cargo transportation*. This involves planning and arranging the actual movement of goods from the sender to the recipient; the forwarder decides which transport modes (road, rail, sea, air) are most suitable, schedules shipments, and ensures the cargo reaches its destination efficiently, safely, and on time.
- *Selecting vehicles and routes*. The forwarder chooses the most appropriate vehicles (trucks, ships, planes, or trains) and plans the best routes for delivery; this requires considering factors like cost, delivery time, cargo type, road or port conditions, and potential risks along the route.

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- *Coordinating the loading and unloading of cargo*. The forwarder supervises the physical handling of goods to ensure safe and proper loading and unloading; this includes making sure cargo is correctly packaged, secured, and handled according to regulations, reducing the risk of damage during transit.
- *Handling documentation (customs procedures, export-import permits)*. Forwarders manage all required paperwork for international shipments; this includes customs declarations, export/import permits, certificates of origin, invoices, bills of lading, and any other legal documentation needed to comply with national and international regulations.
- *Monitoring cargo condition and quality*. Freight forwarders track the condition of the cargo throughout the journey; for sensitive or perishable goods (like food, chemicals, or electronics), they ensure temperature, humidity, or other storage requirements are maintained, and they address any problems that arise during transit.
- *Providing warehousing and cargo distribution services*. Forwarders often offer temporary storage of goods in warehouses and manage distribution to multiple destinations; this may involve consolidating shipments, splitting cargo for different recipients, and organising last-mile delivery.
- *Managing taxes and other shipping-related expenses*. They handle all financial aspects of shipping, including duties, tariffs, taxes, fuel surcharges, insurance, and other logistics-related costs; the forwarder ensures compliance with local and international regulations while optimising costs for the client.

In short, a freight forwarder is like a logistics conductor, coordinating every stage of cargo movement, from planning and paperwork to physical handling and delivery, ensuring goods move efficiently, safely, and legally.

Skiba & Karas (2022) highlight that the forwarding profession is multifaceted and has evolved historically. Initially, it focused on transport organisation on behalf of the client, occasionally including additional services related to border procedures and documentation; however, today, the forwarder is no longer just an intermediary between the sender and carrier; it becomes a key link integrating client and supplier activities within the entire supply chain (Skiba & Karas, 2022). Digitisation and automation are technological tools that facilitate the forwarder's work and help organise the entire transport process more smoothly (Bahatov, 2022). Significant changes are underway, with forwarders expanding their role from executing individual orders to coordinating and organising the entire supply chain (Kanchaveli, 2022).

3. The Role of Warehousing in the Supply Chain

Warehousing is a vital part of the supply chain, encompassing the receipt, storage, and distribution of goods until final consumption (Jarašūnienė, Čižiūnienė & Čereška, 2023). Key issues, such as lack of space, delayed orders, and insufficient advanced technologies, lead to inefficiency and high costs (Tubis & Grzybowska, 2022). Modern warehouses are complex technical structures responsible for storing, processing, and distributing materials among consumers. Proper process management and technological integration are required to prevent problems such as transport congestion, delivery delays, or excessive manual labour.

Main warehouse processes include (Jarašūnienė, Čižiūnienė & Čereška, 2023):

- *Goods receipt and quality control*. This is the first step in warehouse operations, where incoming goods are received, checked, and recorded. Key activities include:
  - Verification – confirming that the shipment matches the purchase order in terms of quantity, type, and specifications.
  - Inspection – checking for damages, defects, or discrepancies.
  - Documentation – recording goods in the warehouse management system (WMS) and updating inventory records.
  - Labelling and tagging – assigning barcodes, RFID tags, or other identifiers to track items accurately.

Proper goods receipt and quality control prevent errors, reduce losses, and ensure that only compliant products enter the warehouse.

- *Warehousing and inventory management*. This process involves storing goods efficiently and maintaining accurate inventory levels. Key tasks include:
  - Storage organisation – allocating space using techniques like racking, pallet stacking, or bin locations to maximise efficiency.

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- Inventory tracking – monitoring stock levels in real-time using WMS, RFID, or barcode scanning systems.
- Stock rotation – implementing methods like FIFO (First-In-First-Out) or LIFO (Last-In-First-Out) to manage product shelf life and minimise spoilage.
- Cycle counting – regularly auditing stock to ensure accuracy and reconcile discrepancies.

Efficient inventory management minimises storage costs and ensures that products are available when needed.

- *Order picking and preparation.* This process involves retrieving products from storage to fulfil customer orders. Key activities include:
  - Order generation – receiving customer orders from ERP or WMS systems.
  - Picking – selecting items from shelves or pallets according to the order. Methods can include batch picking, zone picking, or wave picking.
  - Consolidation and checking – combining items into complete orders and verifying accuracy before packaging.

Proper picking and preparation reduce errors, improve delivery speed, and enhance customer satisfaction.

- *Packaging and dispatch.* This process ensures goods are securely packaged and sent to the correct destinations. Key activities include:
  - Packing – using appropriate materials and methods to protect goods during transit.
  - Labelling and documentation – printing shipping labels, invoices, and customs documents if applicable.
  - Loading and dispatch – coordinating with carriers, arranging transport, and ensuring timely dispatch.
  - Tracking – updating shipment status in the system to provide visibility to customers.

Effective packaging and dispatch processes reduce damage, returns, and delivery delays.

- *Returns processing*. This process handles returned goods from customers efficiently. Key steps include:
  - Inspection and assessment – checking returned items for damage, expiration, or quality issues.
  - Sorting and classification – determining if items can be restocked, repaired, recycled, or discarded.
  - Inventory update – adjusting stock records to reflect returns.
  - Refund or replacement coordination – communicating with customers or sales teams regarding replacements, exchanges, or refunds.

Efficient returns processing reduces losses, recovers value from returned items, and maintains customer trust.

According to Sy (2025), integration refers to the seamless coordination between warehouse operations (storage, inventory management, order preparation) and forwarding activities (transport planning, shipment coordination, documentation, and delivery). By connecting these two core logistics functions, businesses can manage the entire supply chain more efficiently, ensuring goods move smoothly from production to the end customer. The integration of warehousing and forwarding processes ensures a smooth flow of materials from production to the end customer (Sy, 2025; Ahmed, 2025):

- *Information sharing*. Using warehouse management systems (WMS) and transportation management systems (TMS) that communicate in real time, allowing accurate tracking of stock levels, shipment status, and delivery schedules.
- *Process synchronisation*. Aligning warehouse operations with transport schedules to minimise idle time and ensure that goods are ready for dispatch exactly when required.
- *Resource optimisation*. Coordinating labour, storage space, and transport assets to reduce redundancies and increase operational efficiency.
- *Proactive problem solving*. Forwarders and warehouse managers can anticipate delays, shortages, or disruptions and take corrective action before they impact the supply chain.

According to scientific literature, effective coordination of warehouse processes allows to achieve following results:

- *Reduced overall logistics costs*. Optimising storage space and transport routes reduces unnecessary handling, inventory holding costs, and fuel consumption.
- *Avoids duplicate operations*, such as moving goods multiple times due to poor coordination; for example, items might be moved from storage to a staging area multiple times because transport schedules or order preparation are misaligned (Struk & Karpii, 2019). Impact of avoiding duplicates:

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- Reduced handling costs – avoiding unnecessary moves saves money, labour and equipment.
- Minimised risk of damage – fewer moves mean fewer chances for breakage or spoilage.
- Speeded up operations – coordinated workflows ensure that goods go directly from storage to shipment without redundant steps, reducing lead times.
- Improved accuracy – fewer transfers reduce the risk of errors such as sending the wrong items or misplacing stock.

Instead of moving pallets from one warehouse zone to another several times for different shipments, an integrated system schedules loading so items go directly from storage to the outbound truck, cutting extra moves.

- *Bulk consolidation of shipments* minimises transport costs per unit. It involves combining multiple smaller shipments into a single, larger shipment (Wang et al., 2021; Davidenko, Ristvej & Strelcova, 2020). This is a key strategy for cost efficiency in logistics. Benefits of bulk consolidation:
  - Lower transport cost per unit. Shipping a full truck, container, or shipment is generally cheaper per item than sending several smaller shipments separately.
  - Fewer trips required. Consolidation reduces the number of transport trips, saving fuel, labour, and vehicle usage.
  - Reduced environmental impact. Fewer trips mean less carbon emissions, making logistics more sustainable.
  - Better space utilisation. Larger consolidated shipments optimise truck or container capacity, avoiding wasted space.

In short, instead of sending ten partial-load shipments to different customers in the same region, the forwarder consolidates them into one full truckload, splitting the goods at the destination. This reduces overall transport costs while maintaining delivery efficiency.

- *Shortened order fulfilment time*. Orders are picked, packed, and ready for dispatch as soon as production or procurement is complete (Arabelen & Kaya, 2021); real-time inventory visibility ensures the warehouse only prepares items that are actually available, reducing delays (Jarašūnienė, Čižiūnienė & Čereška, 2023); faster response times from integrated systems allow quicker delivery to customers.
- *Improved customer service quality*. Accurate tracking and timely updates provide customers with reliable delivery information; reduced errors in orders (wrong items, missing quantities) increase customer satisfaction (Taletović, 2023); enhanced ability to meet tight deadlines and handle urgent or last-minute orders (Ahmed, 2024).
- *Increased flexibility in response to market changes*. Efficient warehouse coordination supports optimised consolidation, sorting, and staging of goods for shipment, ensuring smooth cargo organisation and flow (Sy, 2025); accurate and timely warehouse data improves route planning decisions, enabling faster and more cost-effective transportation (Bahatov, 2022); coordinated processes ensure timely and accurate preparation of transport and customs documentation, reducing delays and compliance risks (Arunkumar & Meera, 2025); proper synchronisation between warehousing and forwarding facilitates smoother customs clearance through accurate inventory and shipment information (Orłowska & Chackiewicz, 2024); integrated warehouse operations enhance communication and scheduling with carriers, improving transport reliability and capacity utilisation (Wang et al., 2021) (see summarising Table 1 below).

Table 1. Comparison of Forwarding and Warehousing Functions

Forwarding functions:	Warehousing functions:
Cargo organisation (Sy, 2025)	Inventory management (Ahmed, 2024)
Route planning (Bahatov, 2022)	Space optimisation (Taletović, 2023)
Documentation handling (Arunkumar & Meera, 2025)	Goods receipt/issue (Ahmed, 2024)
Customs procedures (Orłowska & Chackiewicz, 2024)	Packaging operations (Jarašūnienė, Čižiūnienė & Čereška, 2023)
Carrier coordination (Wang, Wen, Yip & Fan, 2021)	Order picking (Arabelen & Kaya, 2021)

In short, integration transforms warehousing and forwarding from isolated functions into a cohesive logistics network, aligning information, resources, and processes. This leads to cost savings, faster deliveries, better customer experiences, and greater adaptability – all essential for maintaining competitiveness in today's dynamic market.

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4. Methods of Optimising Warehousing Processes

ABC Analysis – one of the most effective inventory management methods (Tinelli, Vivaldini, & Becker, 2012). ABC Analysis is a method used to categorise inventory items based on their value and importance, allowing businesses to prioritise management efforts on the most critical products (Abdolazimi et al., 2021). The method is based on the Pareto Principle (80/20 rule), which suggests that a small portion of items often accounts for the majority of the value or profit.

Category A: 15-20% of items, generating 70-80% of profit. Management focus:

- Close monitoring and strict control of stock levels.
- Frequent inventory checks (daily or weekly).
- Optimised reorder points to prevent stockouts.
- Use of advanced forecasting techniques.

Even though these items are few, they have a significant impact on overall profitability. Mismanagement can lead to high losses or missed sales opportunities.

Category B: Medium-priority items, 20–30% of total inventory, making approximately 15–20% of total profit. Management focus:

- Moderate control over stock levels.
- Regular review (weekly or bi-weekly).
- Balanced inventory replenishment.

These items are important but not as critical as Category A. Efficient management ensures steady profitability without over-investing resources.

Category C: 60-70% of items, generating 5-10% of profit. Management focus:

- Simplified controls and less frequent monitoring (monthly or quarterly).
- Large stock quantities can be held to prevent stockouts.
- Automated replenishment methods can be used.

These items are low-risk in terms of profitability. Over-managing them can tie up unnecessary resources (see Table 2 below).

Table 2. Application of ABC Analysis in Warehouse Management

Category	Share of Goods	Share of Profit	Management Strategy
A	15-20%	70-80%	Daily monitoring, low inventory
B	20-30%	15-20%	Weekly monitoring, medium inventory
C	60-70%	5-10%	Monthly monitoring, high inventory

Source: Abdolazimi et al. (2021)

Recently, scientific articles investigate other technological systems for warehouse management. Warehouse Management System (WMS), as a comprehensive warehouse management system, can direct a warehouse worker to the exact location of a product using the shortest path, reducing time spent searching for items and minimising handling errors (Yu et al., 2025). Using the integrated business management system of SAP S4HANA, a company can automatically adjust inventory levels based on predicted demand, ensuring that warehouses are stocked optimally and shipments are scheduled efficiently (Nendrambaka, 2023; Orłowska, 2023). Each pallet of goods in a warehouse can have an RFID (automatic goods identification) tag scanned automatically as it moves through the receiving area, updating stock levels in the system without manual input. An AGV (Automated Guided Vehicles) can autonomously transport items from the storage area to the packing station according to real-time orders from the WMS, allowing faster processing with fewer staff (Dehghan et al., 2023), see Table 3 below.

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Table 3. Technological Systems for Warehouse Management

Definition:	Key Functions:	Benefits:
Warehouse Management System (WMS) is a software platform designed to control and optimise warehouse operations, from goods receipt to storage, order picking, and dispatch (Yu et al., 2025).	Real-time inventory tracking and stock visibility. Storage location optimisation and space utilisation. Order management and picking route optimisation. Integration with shipping and transport systems. Reporting and performance analytics.	Reduces errors in order fulfilment. Enhances inventory accuracy. Speeds up warehouse processes. Enables better decision-making through analytics.
SAP ERP/S4HANA is an enterprise resource planning system that integrates all core business processes, including warehouse, finance, procurement, and supply chain management, into a unified platform (Nendrambaka, 2023; Orłowska, 2023).	End-to-end visibility of inventory and supply chain. Automation of procurement, order processing, and invoicing. Real-time reporting and analytics across departments. Facilitates coordination between warehouses, suppliers, and logistics providers.	Eliminates data silos and improves communication. Supports strategic planning and forecasting. Reduces operational inefficiencies. Enhances coordination between warehouse and forwarding operations.
RFID (Radio-Frequency Identification) uses tags and scanners to automatically track and identify products within a warehouse or during transport (Zhang, Lin & Esfahbodi, 2025).	Real-time tracking of inventory items. Quick scanning for goods receipt, picking, and dispatch. Automatic updates in warehouse and transport management systems. Integration with security systems to prevent theft or misplacement.	Reduces manual scanning and paperwork. Increases accuracy and speed of inventory management. Provides better traceability for high-value or sensitive goods. Supports automated processes and analytics.
AGVs (Automated Guided Vehicles) are robotic vehicles used in warehouses to transport goods between storage areas, loading docks, and packing stations without human intervention (Dehghan et al., 2023).	Automated movement of pallets, bins, or containers. Integration with WMS to follow optimised routes. Can work continuously and safely around human operators.	Reduces labour costs and human error. Improves operational speed and throughput. Enhances warehouse safety by minimising manual handling. Supports continuous and scalable warehouse operations.

Sources: Yu et al. (2025); Nendrambaka (2023); Orłowska (2023); Dehghan et al. (2023); Zhang, Lin & Esfahbodi (2025).

In summary, together, these systems create a highly automated, efficient, and intelligent warehouse environment:

- WMS optimises daily warehouse operations.
- ERP/S4HANA connects the warehouse with the broader business ecosystem.
- RFID ensures accurate and fast inventory tracking.
- AGVs automate material handling, reducing manual labour and operational bottlenecks.

In a result it supports faster, more accurate, cost-efficient, and flexible warehouse operations that can respond dynamically to customer demands and market changes.

Choosing the right location for a warehouse is one of the most strategic decisions in logistics. It significantly influences the efficiency, cost structure, and responsiveness of the entire supply chain. Proper warehouse location directly affects (Taletović, 2023):

- Compliance with delivery deadlines – transportation usually represents the largest share of logistics expenses
- Compliance with delivery deadlines – warehouse proximity to markets and transport hubs increases delivery reliability.
- Customer service quality – warehouse location determines how quickly and accurately businesses can respond to customer needs.
- Operational flexibility – a well-chosen location allows the company to adapt to market changes more easily (see Table 4).

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Table 4. Impact of Proper Warehouse Location

Affects:	Benefits:	Outcomes:
Transportation costs	Reduces the distance between suppliers, production sites, and customers. Minimises fuel consumption and vehicle operating costs. Allows consolidation of shipments and more efficient routing. Decreases the need for additional distribution centres.	Substantial cost savings and higher cost-effectiveness of logistics operations
Compliance with delivery deadlines	Shortens lead times. Enables faster order processing and dispatch. Reduces the risk of delays caused by congestion or long-distance transport. Supports just-in-time (JIT) or same-day delivery models	Higher punctuality and more consistent fulfilment of delivery promises
Customer service quality	Ensures quick delivery options (e.g., next-day or same-day). Enhances stock availability through better replenishment. Reduces errors and delays in last-mile logistics. Improves customer satisfaction and loyalty.	Better service performance and stronger competitive positioning.
Operational flexibility	Rapid scaling of operations during seasonal demand peaks. Improved access to labour markets. Greater ability to respond to supply chain disruptions. Better integration with multimodal transport networks (road, rail, air, sea).	Increased resilience and agility across the logistics system.

Sources: based on Taletović, 2023

In short, proper warehouse location enables lower transport costs, faster and more reliable deliveries, higher service quality, and greater operational flexibility.

Several scientific and analytical models support decision-makers in choosing the optimal warehouse location. These methods consider multiple criteria such as cost, distance, demand patterns, and infrastructure. Methods for selecting warehouse location (Thakkar, 2021; Houck et al., 2022):

- TOPSIS method – multi-criteria evaluation. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives by comparing them to an ideal (best-case) and anti-ideal (worst-case) option. It helps define criteria (cost, distance, labour availability, infrastructure, etc.), normalise and weight the criteria, calculate each location's distance from the ideal and anti-ideal solution, select the location closest to the ideal option.
- Gravity centre model – geographical optimisation. A mathematical model that identifies the optimal geographic point for a warehouse based on the distribution of customers, suppliers, and transportation flows. It plots customer/supplier locations on a coordinate map, weights each point by demand or shipment volume, and calculates the "centre of gravity" that minimises total distance or transport cost.
- AHP method – analytic hierarchy process. A structured multi-criteria decision-making method that breaks complex problems into a hierarchy of criteria and subcriteria (Manik, 2023; Bingqing & Liting, 2020). It helps define main criteria (cost, accessibility, workforce, risk, etc.), perform pairwise comparisons to determine the importance of each criterion, calculate weighted priority scores, and evaluate each potential location accordingly.

Decision methods such as TOPSIS, the Gravity Centre Model, and AHP help organisations systematically evaluate and select locations, ensuring optimal logistics performance and long-term competitiveness. TOPSIS Handles many criteria simultaneously, provides clear ranking of location alternatives, is suitable for complex decision environments; Gravity Center Model is simple and intuitive, effective for distribution networks, minimises total transportation distances, however, it does not consider qualitative factors (e.g., infrastructure, regulations), and assumes flat geography and equal transport conditions; finally, AHP method incorporates both – quantitative and qualitative – factors, captures expert judgment through pairwise comparisons, offers transparent and logical decision-making structure.

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5. The Integrated Model for Improving Forwarding and Warehousing Services

Implementing recent technological capabilities creates a smarter, faster, and more efficient logistics and warehouse system – real-time data exchange, automation, reduced errors, and optimised resource use collectively improve operational performance, lower costs, and enhance customer satisfaction (Kurniadi, 2025; Kanchaveli, 2022, Zemmouvhi-Ghomari, 2025), see Table 5 below.

Table 5. Technological Convergence of Forwarding and Warehousing Services

Technological advantages	Applications	Benefit
Real-time data exchange – the continuous and instantaneous sharing of information between systems, departments, and supply chain partners.	Tracking inventory levels across multiple warehouses. Monitoring shipment status during transport. Sharing updates between suppliers, logistics providers, and customers. Integration with ERP, WMS, and transport management systems.	Immediate visibility into inventory and shipment status. Faster decision-making and proactive problem-solving. Reduced delays caused by miscommunication. Enhanced coordination across the supply chain.
Automated process management - the use of software and technology to automatically perform routine logistics and warehouse tasks.	Automated order picking and sorting. Dynamic route optimisation for deliveries. Scheduling replenishment and stock transfers. Automated documentation and customs compliance.	Faster and more consistent operations. Reduced reliance on manual labour for repetitive tasks. Improved throughput and operational efficiency. Allows staff to focus on strategic or value-added activities.
Reduced human error – minimising mistakes caused by manual handling, data entry, or communication lapses through automation and digital systems.	Barcode and RFID scanning for inventory accuracy. WMS-guided picking and packing instructions. Automated reporting and documentation. AI-driven forecasting to reduce planning errors.	Fewer stock discrepancies and shipping mistakes. Increased order accuracy and customer satisfaction. Reduced operational costs associated with errors. Lower risk of compliance or safety violations.
Better resource utilisation - optimising the use of warehouse space, labour, equipment, and transportation through technology.	Dynamic storage allocation using WMS. Scheduling and routing optimisation for delivery vehicles. Real-time allocation of labour based on workload. Monitoring and maintenance of equipment to maximise uptime.	Maximised storage and transport efficiency. Reduced operational waste and costs. Improved staff productivity. Greater flexibility to respond to changes in demand.

Sources: based on Kurniadi (2025); Kanchaveli (2022)

AI technologies are increasingly integrated into logistics and warehouse operations to enhance efficiency, accuracy, and decision-making (Krnjaic et al., 2024; Rad et al., 2025), see Table 6 below.

Table 6. Applications of Artificial Intelligence Solutions in Logistics

AI solution:	Applications:	Benefit:
Demand forecasting – using AI algorithms to predict future customer demand based on historical data, market trends, and external factors	Anticipating product demand for accurate inventory planning. Optimising stock levels to reduce shortages or overstock. Supporting dynamic pricing strategies. Forecasting seasonal or regional fluctuations.	Minimises stockouts and excess inventory. Reduces holding costs and waste. Enables proactive supply chain planning.
Route optimisation – AI-powered algorithms analyse multiple factors to determine the most efficient delivery routes.	Planning optimal routes for trucks, AGVs, or drones. Adjusting routes in real-time based on traffic, weather, or delays. Coordinating multi-stop deliveries and pickups. Integrating with WMS and transport management systems.	Reduces fuel and transportation costs. Shortens delivery times and improves punctuality. Enhances driver and fleet productivity. Improves customer satisfaction with timely deliveries.

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Inventory management – AI systems help manage inventory dynamically, including stock replenishment, storage allocation, and product tracking.	Predictive restocking based on demand and lead times. Automated warehouse slotting to optimise space utilisation. Identifying slow-moving, fast-moving, or seasonal items. Integrating with WMS and RFID systems for real-time updates.	Maintains optimal stock levels. Reduces carrying costs and storage inefficiencies. Minimises human error in inventory handling. Supports agile response to market changes.
Risk identification – AI analyses internal and external data to detect potential risks and disruptions in the supply chain.	Predicting delays in shipments or supplier failures. Monitoring fluctuations in fuel, material, and labour costs. Identifying regulatory or compliance risks. Detecting anomalies in warehouse or transport operations.	Enables proactive mitigation of supply chain disruptions. Improves decision-making and operational resilience. Reduces financial and reputational risks. Enhances overall supply chain reliability.

Sources: based on Krnjaic et al. (2024); Rad et al. (2025)

AI transforms logistics by providing predictive insights, real-time optimisation, and risk intelligence. Its applications in demand forecasting, route optimisation, inventory management, and risk identification allow organisations to reduce costs, improve service quality, and increase operational flexibility.

Table 7. Integrated Risk Management Strategic Guidelines

Risk Type	Forwarding Impact	Warehousing Impact	Preventive Measures
Supply delays	Route changes	Inventory shortage	Alternative suppliers, safety stock
Technical failure	Data loss	Process stoppage	Backup systems, data recovery
Demand fluctuations	Transport under/overuse	Space under/overuse	Flexible planning, dynamic management

Source: based on Singh, Chaudhary & Saxena (2018)

Common risk sources (Hanafiah et al., 2022; Kahya, Huschbeck & Markovič, 2025):

- *Supply chain deficiencies* refer to weaknesses, disruptions, or inefficiencies in the flow of materials, information, or financial resources across the supply chain. These risks can arise from internal processes, external partners, or environmental factors. In includes supplier unreliability (delays, quality issues, inability to meet demand), poor coordination or lack of real-time data sharing between suppliers, manufacturers, and logistics providers, insufficient inventory, when stockouts are caused by inaccurate forecasting or inadequate safety stock, transportation issues, including carrier delays, congestion, or infrastructure failures, and, finally, even natural disasters or geopolitical events, such as floods, earthquakes, strikes, or political instability disrupting supply flows.
- *Technological disruptions* involve failures, malfunctions, or cyber-related incidents in the digital systems that support logistics operations. As warehouses and transport networks become more automated, these risks increase. It includes system failures – downtime in WMS, TMS, ERP, or barcode/RFID systems; cyberattacks, ransomware, data breaches, or hacking targeting logistics platforms; automation failures (malfunctioning AGVs, robots, conveyors, or sorting machines), integration issues or problems when connecting new technologies (IoT, AI, cloud systems) with existing infrastructure, and, communication breakdowns, that result in loss of connectivity between devices, sensors, or tracking systems.
- *Price fluctuations* involve unpredictable changes in the cost of transportation, fuel, raw materials, labour, or other logistics-related expenditures. These changes may be driven by market conditions, geopolitical tensions, or supply-demand imbalances. Fuel price volatility directly affects shipping costs for trucks, ships, and airplanes; raw material price changes affect production schedules and inventory strategies; currency exchange rate fluctuation influences cost of imports and exports; labour cost increases can raise warehousing and transport costs; seasonal demand spikes lead to higher freight rates.
- *Regulatory changes* refer to modifications in laws, standards, trade agreements, customs requirements, and industry regulations that affect logistics operations. New customs laws or tariffs affect import/export procedures and cost structures; environmental regulations put restrictions on emissions, fuel types, or packaging materials; safety standards establish requirements for handling hazardous materials or workplace safety in warehouses; labour regulations affect changes in working hours,

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overtime rules, or employee protections; and finally, trade policy shifts create new free-trade agreements or trade barriers.

Based on theoretical analysis (Davidenko, Ristvej & Strelcova, 2020; Arabelen & Kaya, 2021; Fares, 2025; Unterkalmsteiner, & Gorschek, 2023), there are two main priorities for improving forwarding services – process optimisation and human resource management (see Table 8 below).

Table 8. Priorities for Improving Forwarding and Warehousing Services

Technology Implementation:	Process Optimisation:	Human Resource Development:
Development of digital platforms. Deployment of automation solutions. Enhancement of data analytics.	Application of "Lean" logistics principles. Development of standardised procedures. Continuous improvement.	Employee training. Motivation systems. Teamwork promotion.

Source: based on Davidenko, Ristvej & Strelcova (2020); Arabelen & Kaya (2021); Unterkalmsteiner, & Gorschek (2023); Fares (2025)

The integrated model to enhance forwarding and warehousing services through technological convergence, AI integration, risk management, and targeted improvements in processes and human resources, based by sources like Kurniadi (2025), Kanchaveli (2022), and others, emphasises real-time data exchange, automation, error reduction, and resource optimisation to boost efficiency, cut costs, and improve customer satisfaction. It highlights four core technologies (see Table 5 above):

- *Real-time data exchange* – enables tracking, monitoring, and ERP/WMS integration for immediate visibility, faster decisions, and better coordination.
- *Automated process management* – automates picking, routing, scheduling, and documentation, speeding operations and freeing staff for strategic tasks.
- *Reduced human error* – uses scanning, guided systems, and AI forecasting to minimise discrepancies, boost accuracy, and lower costs.
- *Better resource utilisation* – optimises space, labour, equipment, and transport via dynamic allocation and monitoring, enhancing flexibility and reducing waste.

Based on Krnjaic et al. (2024) and Rad et al. (2025), artificial intelligence solutions may be used to transform operations through predictive and optimisation tools (see Table 9 below).

Table 9. Integrated Model for Improving Forwarding and Warehousing Services

Artificial Intelligence Solutions:	Key Application:	Primary Benefits:
Demand forecasting	Inventory planning, dynamic pricing	Minimises stockouts/overstock, cuts holding costs
Route optimisation	Real-time adjustments, multi-stop coordination	Reduces fuel/delivery times, improves punctuality
Inventory management	Predictive restocking, slotting	Optimises stock, reduces errors and costs
Risk identification	Delay prediction, anomaly detection	Enhances resilience, lowers financial risks

This model holistically integrates tech and management for resilient, efficient logistics, prioritises two areas (Davidenko, Ristvej & Strelcova, 2020; Arabelen & Kaya, 2021; Fares, 2025; Unterkalmsteiner, & Gorschek, 2023) – process optimisation (Lean principles, standardised procedures, continuous improvement) and human resource development (training, motivation, teamwork), and outlines integrated guidelines (Singh *et al*., 2018), addressing risks like supply delays, technical failures, and demand fluctuations through preventive measures such as backups and flexible planning.

Conclusions

The conducted research confirms that forwarding and warehousing services are no longer independent logistics functions but interdependent components of an integrated supply chain system that significantly influences operational efficiency, cost effectiveness, and customer satisfaction. Integration of forwarding and warehousing is critically important for comprehensive logistics efficiency (Struk & Karpii, 2019; Sy, 2025). In the context of globalisation, increasing trade volumes, and technological transformation, the integration of these services becomes a critical prerequisite for maintaining competitiveness and ensuring sustainable

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economic development. Technological transformation is a key competitive factor (Kurniadi, 2025; Bahatov, 2022):

- automation reduces operational costs;
- digitisation improves visibility and control;
- artificial intelligence allows proactive risk management;

Strategic approach to warehouse location and layout directly influences (Taletović, 2023):

- transport costs;
- service speed;
- customer satisfaction.

The theoretical analysis demonstrates that forwarding services have evolved from a narrowly defined transport-organising role into a comprehensive supply chain coordination function. Continuous improvement and adaptability to changing market conditions ensure long-term competitive advantage (Arabelen & Kaya, 2021; Zemmouchi-Ghomari, 2025). Modern freight forwarders act as integrators, managing transportation, documentation, customs procedures, warehousing coordination, and information flows. At the same time, warehousing has transformed into a technologically advanced logistics hub responsible not only for storage but also for inventory optimisation, order fulfilment, value-added services, and real-time data generation. The effectiveness of each function is therefore highly dependent on the quality of coordination between them.

The study identifies key factors affecting the performance and integration of forwarding and warehousing services, including information transparency, process synchronisation, resource utilisation, technological maturity, and human resource competence. Inefficient coordination leads to duplicated operations, increased handling costs, longer lead times, and reduced service quality. Conversely, integrated management enables bulk shipment consolidation, faster order fulfilment, reduced logistics costs, improved customer service, and greater flexibility in responding to market changes.

A central contribution of this research is the development of an integrated conceptual model for improving forwarding and warehousing services. The model is based on four core technological pillars: real-time data exchange, automated process management, reduction of human error, and optimised resource utilisation. These pillars are supported by advanced digital solutions such as WMS, ERP/SAP S4HANA, RFID, AGVs, and artificial intelligence applications. AI-driven demand forecasting, route optimisation, inventory management, and risk identification significantly enhance decision-making accuracy, operational resilience, and adaptability under uncertainty. The research also emphasises the importance of integrated risk management. Supply chain disruptions, technological failures, demand fluctuations, price volatility, and regulatory changes pose substantial risks to logistics operations. The proposed model incorporates preventive and corrective measures, including safety stock strategies, alternative routing, backup IT systems, flexible planning, and proactive monitoring, thereby strengthening the robustness of forwarding and warehousing systems.

In addition to technological integration, the study highlights two strategic priorities for long-term improvement: process optimisation and human resource development. The application of Lean logistics principles, standardised procedures, and continuous improvement initiatives enhances operational consistency and efficiency, while targeted employee training, motivation systems, and teamwork development ensure effective use of advanced technologies and support organisational learning.

In conclusion, the integrated model proposed in this study provides a holistic, practitioner-oriented framework for improving forwarding and warehousing services. By aligning technological solutions, operational processes, risk management practices, and human resources, the model contributes to higher service quality, lower logistics costs, increased reliability, and enhanced customer satisfaction. The results offer both theoretical value for logistics and supply chain research and practical guidance for logistics service providers seeking to modernise operations and strengthen their competitive position in dynamic market conditions. Strategic recommendations are focused on adaptation of the model via phased implementation – integrate WMS/ERP with AI for operations, prioritise ABC analysis and AGVs for warehousing, and build cross-functional teams for forwarding. Future research should validate through case studies, focusing on emerging

tech like advanced IoT amid geopolitical risks. This framework not only resolves current inefficiencies but also scales for economic growth in logistics-dependent economies.

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SECURITY, POWER AND EUROPEAN STRATEGIC AUTONOMY IN A TRANSFORMING GLOBAL ORDER

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Abstract. This article examines the evolving relationship between politics and security in an era characterised by increasing power rivalry, multipolar competition, and strategic uncertainty. The author argues that contemporary security dynamics can no longer be understood within traditional state-centric or purely military frameworks, as power is increasingly exercised through economic interconnectedness, technological control, regulatory influence, and informational superiority. It employs an interdisciplinary approach, drawing from security studies, international relations, and political theory, to analyse how globalisation has transformed security into a competitive and perpetually contested domain. Particular attention is paid to the European Union, which currently faces the dual challenge of heightened external vulnerability and internal pressure to preserve its normative identity. In this context, the author examines the concept of European strategic autonomy as a response to weaponised interdependence and hybrid forms of power, critically assessing its limits and contradictions. Through the reconceptualisation of power, authority, and competition, the article contributes to ongoing theoretical discourse on European security and offers a nuanced framework for understanding security governance in a transforming global order.

Keywords: security; power transformation; European strategic autonomy; multipolar global order; strategic uncertainty; weaponised interdependence

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Additional disciplines: Security, Defence, International Relations

1. Introduction

In the current era of strategic uncertainty and a rapidly shifting global order, the scholarly examination of the relationship between politics, security, and international relations is acquiring renewed significance. The continuous deterioration of both the global and regional security environment, including the war in Ukraine, armed conflicts in the Middle East, and growing tensions in the Indo-Pacific region, clearly demonstrates that the international system is confronting a series of complex and interconnected crises. These crises threaten not only the stability of individual states but also the very foundations of the liberal international order. These events and phenomena do not occur in a vacuum; rather, they are deeply embedded within the broader structure of globalised multipolar competition, which is disrupting traditional notions of sovereignty, power, and security.

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The conflict in Ukraine has become a paradigmatic example of the open violation of the European security architecture (Graham, 2024; Ivančík & Andrassy, 2025; Bond, 2025). Concurrently, it serves as a clear manifestation of the hybrid nature of contemporary threats, which encompass: cyber-attacks on both public and private institutions; the misuse of social media and digital platforms for disseminating disinformation, conspiracy theories, and manipulating public opinion; economic coercion; the weaponisation of energy flows; and other activities that combine conventional and unconventional methods and tactics, legal and illegal instruments and mechanisms, as well as regular and irregular forces and means (Ivančík & Andrassy; 2024; Ivančík et al., 2024). Furthermore, the parallel conflict between Israel and Hamas in the Gaza Strip illustrates how regional crises can easily escalate into globally sensitive security dilemmas (Hassoun et al., 2025; Batool, 2025). The common denominator of these phenomena is the breakdown of traditional power balances and the weakening effectiveness of international norms and institutions, which creates a permissive environment for the aggressive strategies of great powers and non-state actors.

Globalisation, initially celebrated as a source of prosperity and integration, has increasingly revealed itself in recent years to also be a vector for fragmentation, disciplining, and vulnerability. Hybrid threats, the strategic weaponisation of interdependence as a tool of coercion, and the return of overt geopolitical rivalry are symptoms of a new power order in which the instruments of power are dispersed across state, transnational, and technological actors. The very technologies and interconnections that once strengthened cooperation are now frequently being turned into tools for political dominance and repression (Farrell & Newman, 2019; Suter & Ziltener, 2024).

The contemporary epoch is characterised by increasingly pronounced multipolarity and the emergence of new power centres that challenge the West's current dominance in international security and political normativity. The rise of China, the revisionist ambitions of Russia, the growing assertiveness of Turkey, and the fragmentation of transatlantic unity all provide evidence that traditional power alliances are being severely tested. Europe—as a space of both internal integration and geopolitical vulnerability—thus finds itself at the epicentre of this global transformation. Therefore, the security and political reflection on this situation necessitates a new research approach that integrates theoretical concepts with an analysis of power, authority, and competition within an interconnected international sphere.

Simultaneously, the very concept of security is undergoing a reconfiguration. From a classically understood military-strategic concept, security is evolving into a fluid, multidimensional, and often subjectively perceived framework. Within this framework, not only states but also non-state actors, transnational organisations, technology companies, and information networks are playing increasingly crucial roles (Breslin & Nesadurai, 2018; Balarabe, 2025). Politics and security are no longer isolated spheres; they are increasingly intertwined through mechanisms such as strategic narratives, digital dominance, energy dependency, and economic coercive diplomacy (Dirma et al., 2024; Okunevičiūtė et al., 2025).

The current international reality therefore necessitates a fresh academic perspective on the interplay among politics, security, and international relations, especially within the European context. This calls for a critical, interdisciplinary, and theoretically grounded approach that analyses how the forms of power and authority are changing in an era of hybrid threats, strategic uncertainty, and globalised competition. This article aims to provide precisely such a reflection, to offer a systematic and theoretically informed analysis of these relationships, focusing on European contexts, risks, and transformative trends.

Our research is grounded in the premise that the scholarly examination of the relationship between politics, security, and power has evolved since the end of the Cold War in close conjunction with shifts in the global order, technological development, and the changing nature of threats. Traditional realist and neorealist concepts, represented by authors such as Mearsheimer (2014), emphasised the centrality of the state, military force, and the anarchical structure of the international system. Conversely, constructivist approaches broadened the understanding of security to include identity, norms, and the socially constructed meanings of threats. The approach of the Copenhagen School (Buzan, Wæver & de Wilde, 1998), which introduced the concept of securitisation as a process of discursively constructing threats, has been particularly influential in this context.

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The literature dedicated to power has also diversified. In addition to the classic distinction between hard power and soft power (Gallarotti, 2010), new concepts have emerged in the last decade, such as sharp power (Walker, 2018; Walker et al., 2020), connectivity power (Leonard, 2021), and weaponised interdependence (Farrell & Newman, 2019), which reflect the transformation of power instruments in a globalised, digitally interconnected world. Scholars like Barnett and Duvall (2005) and Lukes (2021) have sought to develop multidimensional typologies of power, encompassing not only material resources but also symbolic dominance, normative frameworks, and the capacity to shape the preferences of others.

In the sphere of European security, particular significance is attached to works that analyse the EU as a normative, regulatory, or post-sovereign actor. Manners (2002) introduced the concept of Normative Power Europe, while authors such as Bickerton et al. (2015), Lippert et al. (2019), and Beaucillon (2023) discuss the possibilities and limitations of strategic autonomy. Standing out from the literature on hybrid threats are works by Ferrag et al. (2023), Borch and Heier (2024), and Ivančík and Nečas (2025), which identify new forms of threats and destabilisation in the digital and informational space.

In light of the above, it can be concluded that the available literature, while extensive, provides fragmented knowledge regarding security, authority, and power within the European and global context. For this reason, this article seeks to synthesise these findings, extend them with new analytical concepts, and demonstrate how the nature of security reasoning is changing under conditions of strategic uncertainty, hybrid threats, and globalised power competition.

The objective of this academic article is to examine the relationships between politics, security, and international relations within the European context, with attention to the shifting global environment characterised by strategic uncertainty, power rivalry, and escalating hybrid threats. On a methodological level, the article is primarily based on a qualitative research approach that combines critical analysis of scholarly sources, discursive analysis, and comparative geopolitical reflection. It employs interdisciplinary frameworks from political science theory, security studies, international relations, and critical geopolitics. The research questions are addressed through an analytical-synthetic procedure that links empirical observations with conceptual frameworks.

The structure of the article is divided into four thematic chapters and a conclusion. The first chapter analyses the relationship between politics and security in the environment of globalised multipolar competition. The second chapter focuses on the specifics of the European context and the tension between strategic autonomy and great power rivalry. The third chapter provides a theoretical reflection on the concepts of power, authority, and competition, while the fourth chapter examines the reconceptualisation of political authority in the context of globalised challenges. The concluding section summarises the main findings and formulates normative considerations concerning the direction of European security policy in a dynamically changing international environment.

2. Security and Politics under Conditions of Globalised Multipolar Competition

Globalisation, which can be understood as a set of deepening transnational interconnections and an acceleration of the exchange of goods, capital, information, and people, has fundamentally transformed the frameworks within which power, security, and politics are conceived.

The state is not excluded from this environment, yet its role is shifting. Neoliberal globalisation does not displace the state but rather reconfigures it, from an actor of direct governance to an actor ensuring the conditions for ‘competitiveness’ on a global scale. This normative pressure is reflected in the politics of the ‘state as a firm’, that is, in understanding governance as the management of competition, the optimisation of performance, and the internationalisation of regulatory standards (Scholte, 2008).

However, parallel to economic globalisation, a transformation is also underway in the field of security. In an era of multipolar competition, the politics of security is becoming an arena where the power interests of actors

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such as the USA, China, Russia, the EU, and others intersect. In contrast to the post-war bipolarity or the unipolarity of the 1990s, the contemporary security environment is characterised by fluid alliances, a competition of norms, and asymmetric instruments of power (Acharya, 2014). Furthermore, multipolarity is not manifesting solely in the traditional military-strategic sphere, but also in the technological, cyber, informational, and economic domains.

Competition between great powers under conditions of globalisation is no longer primarily about controlling territory but about controlling flows—of data, capital, energy, technologies, and narratives (Farrell & Newman, 2019). This new form of geopolitical competition results in security tools becoming an inseparable part of economic and technological policy—ranging from embargoes and sanctions to the control of chip exports and the shaping of technological standards and cyber alliances (Leonard, 2021; OECD, 2025).

In this context, security policies are increasingly acquiring a 'competitive character'—not as a means of defence against attack, but as a tool for strategic dominance, containment of others' influence, and the enforcement of one's own standards and preferences. As Ikenberry (2018) argues, the current great power competition is not just military, but ideological, normative, and technological, with the core of the conflict being the question of who defines the rules of the global order.

The term 'competitiveness' has acquired a new meaning in the political-security discourse following the Cold War. Originally an economic term, it has become a metapolitical principle under the influence of neoliberal governance, redefining the state's objective function—not as a steward of the collective good, but as an 'entrepreneur on behalf of the national interest' (Slobodian, 2018). A state conceptualised in this manner strives to optimise its position in the global order, not only through economic means but increasingly through security means, thereby blurring the lines between economic policy and security strategy.

In this context, a fundamental transformation of the concept of security is taking place. According to Buzan et al. (1998), security is no longer limited to military defence but expands into the domains of political stability, economic performance, technological sovereignty, societal cohesion, and environmental threats. Security thus becomes a multidimensional and constantly securitised agenda, an object of competitive discourse between states, where nearly any issue is potentially subject to a security solution (Balzacq, 2011).

The multipolar environment further deepens this development. In the absence of a dominant hegemon, the frequency and intensity of security competition increase—not as open conflict, but as a series of races in the fields of innovation, influence, legitimacy, and norm-setting. Contemporary competition is not merely economic or military; it is a 'competitive logic' framing the entire international order, which transforms even peaceful relations into competitive and hierarchical ones.

This phenomenon has fundamental implications for the European space. European states, which historically founded their security on institutionalised cooperation and normative power (Manners, 2002), today face the challenge of adapting to an environment where soft power is systematically questioned, and where strategic autonomy cannot be achieved without building proprietary capabilities and capacities (Fiott, 2025). Security policy has thus returned to the centre of political discourse, not as a marginal or technical matter, but as the main instrument for survival and self-assertion in a competitive world.

One of the principal consequences of globalised multipolar competition is the growing need for a fundamental revision of strategic thinking. This thinking can no longer be based exclusively on the logic of traditional realism but must reflect the complexity and interconnectedness of new security threats and challenges. In an environment where security, competitiveness, and geopolitical influence are increasingly intertwined, it ceases to be possible to think about defence and stability separately from economic, technological, ecological, or societal dimensions. Security policy thus becomes an ever more pronounced dimension of every significant public policy, from industrial to educational, and politics itself acquires a security character through the so-called securitisation of identity, values, and performance within the international system (Balzacq, 2011).

This trend leads to the erosion of classical dichotomies that shaped strategic thinking throughout the greater part of the 20th century—such as war versus peace, threat versus challenge, or risk versus opportunity. Currently,

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these concepts are overlaid by hybrid dynamics, which combine elements of military, cyber, informational, energy, and economic power into fluid, difficult-to-predict forms of operation (Caliskan, 2019; Mumford, 2020). For instance, economic sanctions, which once served a supplementary role in foreign policy, are now becoming a key instrument of geostrategic coercion. Similarly, technological dependence—for example, in semiconductors, artificial intelligence, or cloud infrastructures—is increasingly understood as a strategic vulnerability that can be mobilised as a tool of power if required (Mayer & Lu, 2025; Reinhold, 2025).

The response to these challenges, therefore, requires complex, adaptive, and systemically interconnected strategies that can account for multiple dimensions of security simultaneously. This entails integrating a security perspective into policies concerning digital transformation, climate adaptation, energy transition, or economic diplomacy, areas that were until recently considered 'technocratic' or 'neutral' (Bremmer, 2022). Political decision-making must thus adopt 'strategic thinking in horizons of uncertainty', the ability to anticipate the indirect consequences of crises and to formulate policies with an awareness of the competitive logic that is increasingly penetrating all spheres of the global order.

Europe finds itself in a particularly complex position in this process. On the one hand, it faces the need to strengthen its capabilities and capacities in strategic autonomy, technological sovereignty, and resilience against external pressures. On the other hand, it strives to preserve the normative values that historically defined it as an area of peace, rule of law, and multilateralism (Manners, 2002; Fiott, 2025). This tense equilibrium between competition and cooperation, between power and law, between autonomy and interconnectedness, will continue to define the parameters of European security policy in the 21st century (Desmaele, 2025; Fiott, 2025).

As current academic literature shows, if the political and security reflection on global competition is to be effective, it must be multidimensional, interdisciplinary, and normatively conscious. It is not only about defending territory but also about protecting the fundamental democratic values, institutions, and identity that European societies have built since the Second World War. It is about formulating a policy capable of responding to unpredictable changes without losing its legitimacy and ethical integrity—in short, a policy that is not only efficient and effective but also value-anchored.

3. European Strategic Autonomy Amid Global Power Rivalry

In recent years, the European Union has found itself at the heart of a shifting geopolitical space, forcing it to redefine its position, strategic ambitions, and instruments of action. Despite the EU's long-standing self-portrayal as an actor founded on norms, multilateral rules, and 'soft power' (Manners, 2002), it faces increasing pressure to adapt to the reality of multipolar competition. In this new reality, merely promoting values is insufficient; defending one's own interests is essential.

The catalyst for this shift was primarily the Russian invasion of Ukraine in 2022, which disrupted the fundamental premises of the European security architecture (Graham, 2024; Ivančík & Andrassy, 2025; Bond, 2025). It became apparent that the security the EU had long outsourced to NATO and transatlantic ties is not guaranteed in an environment where great powers employ military force, hybrid operations, and economic weapons as foreign policy tools. The result is a gradual, albeit ambivalent, movement towards building strategic autonomy—the capacity to act independently, collectively, and effectively in the realm of security and defence (Fiott, 2025).

The concept of strategic autonomy has become one of the central points of European debate since 2016, notably following the UK's departure from the EU and during the presidency of Donald Trump, who questioned the meaning of transatlantic ties. Strategic autonomy was initially understood predominantly in the defence domain—as the EU's capacity to act autonomously in the absence of the United States. However, it gradually acquired a broader meaning, encompassing economic and technological sovereignty, energy security, the capacity to respond to disinformation, and geopolitical resilience (Lippert et al., 2019).

On the other hand, this strategy is being forged amidst increasingly intense great power rivalry. The US, China, and Russia are vying for global influence, placing the EU in a complex position: on one side, it is firmly anchored within NATO; on the other, it is conscious of its reliance on the American security guarantee.

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Simultaneously, it faces growing pressure from China, particularly in technological standards, investments, and disinformation campaigns (Esteban et al., 2025).

This reality compels the EU to balance between the pursuit of autonomy and the necessity of cooperation. The EU finds itself in a 'geopolitical squeeze,' forcing it to act strategically, yet without an adequate power base (Bogdanos, 2025). The response has included several initiatives, such as the European Defence Fund (EDF), Permanent Structured Cooperation (PESCO), the Strategic Compass (2022), and ambitions to expand its so-called civil-military capabilities and capacities.

The increasing intensity of strategic rivalry among great powers has led to a fundamental change in the perception of globalisation. While in previous decades economic interconnectedness was viewed as a factor of stability and cooperation, the present shows its reverse side, globalisation has become a source of vulnerability, and interdependence has transformed into a means of coercion (Cerny, 2009; Mazzar, 2022). This phenomenon is often termed in contemporary literature as *weaponised interdependence* (the transformation of interdependence into a tool of coercion, or interdependence as a weapon). In practice, this refers to a situation where states utilise their central position within global networks—for instance, in financial flows, technological infrastructure, or logistical chains, as an instrument of geopolitical pressure (Farrell & Newman, 2019).

The European Union, which had long been one of the greatest proponents of globalisation, finds itself in a highly vulnerable position in this new environment. Dependence on chip supplies from Taiwan, vulnerability to Chinese dominance in critical raw materials, and Russian influence on the European energy market in the years preceding the invasion of Ukraine revealed that economic openness without a geopolitical strategy can be a strategic deficit. Supply chain crises during the COVID-19 pandemic only deepened the awareness of the need to increase resilience and diversification, not only in the economic sense but also in terms of security and technology (European Commission, 2023).

In response to these challenges, the EU began to promote the concept of *open strategic autonomy*. This is an effort to reconcile the principle of economic openness with the capacity to act independently in key areas, such as defence, healthcare, digital infrastructure, and energy. This approach is founded on the premise that autonomy and interconnectedness need not be mutually exclusive, provided that interdependence is symmetrical, controllable, and does not lead to unilateral vulnerability (Damen, 2022; Schmitz & Seidl, 2022).

However, interdependence when weaponised or used for coercion also creates new tensions within the EU. This phenomenon directly follows the broader trends of security's transformation into a competitive and permanently securitised agenda, as elaborated in the first part of the article. States with diverse economic models (Cabelkova et al., 2021) and divergent geopolitical priorities differ in how they interpret the balance between autonomy and integration. While France advocates for stronger EU defence sovereignty and industrial capacity, other countries, such as Germany and Central and Eastern European states—prioritise the transatlantic link and a liberalised trade model. This diversity complicates the building of a unified European approach to geopolitical challenges (Alcidi et al., 2023; Juncos & Vanhoonacker, 2024).

In an effort to reinforce its geopolitical relevance, the European Union strives to consolidate existing foreign, security, and defence policy instruments. Despite limited competencies in common defence, the EU is attempting to acquire a more strategic posture through several initiatives. A significant step was the adoption of the Strategic Compass for Security and Defence in 2022, a document that systematically defines, for the first time, the EU's ambitions in defence, security, and crisis response. The Compass stresses the need to enhance the level of European defence capabilities and capacities, the necessity of rapid reaction (e.g., the creation of the 'EU Rapid Deployment Capacity'), improvement of military mobility, and coordination in cyber defence and space (European Council, 2022).

In response to escalating geopolitical tensions, particularly due to ongoing Russian aggression in Ukraine and uncertainty regarding transatlantic cooperation, the European Union presented the ambitious ReArm Europe initiative in 2025, later renamed Readiness 2030. This plan aims to mobilise up to €800 billion to strengthen the

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defence capacities of Member States, support joint procurement, and invest in key technologies such as drones, cyber defence, quantum technologies, and military mobility (Clapp et al. 2025).

Part of this plan includes the new Security Action for Europe (SAFE) financial instrument, which provides €150 billion in the form of low-interest loans for common defence projects, thereby supporting more efficient use of resources and reducing dependence on external suppliers (European Commission, 2025). Parallel to this plan, the EU adopted the Cyber Solidarity Act in December 2024, which entered into force in February 2025. This legislative act introduces an EU-wide framework for the detection, preparedness, and response to cyber threats, including the establishment of a network of national and cross-border cyber centres and an early warning system (European Union, 2025).

These initiatives represent a significant shift in the EU's approach to security, where emphasis is placed not only on traditional military capabilities and capacities but also on strategic autonomy, regulatory sovereignty, and democratic integrity. At the same time, they reflect the need for a proactive and value-anchored approach to security challenges, one that involves not only state institutions but also civil society and other non-state actors. Alongside these developments, other established formats of cooperation, such as Permanent Structured Cooperation (PESCO) and the European Defence Fund (EDF), continue to evolve, serving as the basis for the collective development of military capacity and support for the defence industry within the EU. However, these instruments face limitations in the form of differing strategic cultures among Member States, uneven distribution of industrial capacities, and long-term dependencies on non-European partners, primarily the USA (Mejino-López & Wolff, 2025; Ivančík & Andrassy, 2025).

Despite these challenges, there has been increasing emphasis in recent years on building civilian and technological autonomy, which is intended to serve as a supporting pillar for strategic autonomy (Anghel et al., 2020). The EU is investing in research, digitalisation, cybersecurity, and artificial intelligence, becoming increasingly aware that technological dependence on third countries poses a risk not only to economic sovereignty but also to the capacity to act independently in crisis situations (Ramahandry et al. 2021; Bria et al., 2024).

The geopolitical environment also forces the EU to address its relationship with NATO, the United States, and strategic partnerships outside the Western world. The transatlantic link remains a crucial guarantee of collective defence. Simultaneously, the EU seeks to increase its own operational capacity in strategic communication, hybrid threats, cybersecurity, and resilience against disinformation. In this context, the need to build complementarity between the EU and NATO, rather than competition, is often highlighted (Ewers-Peters, 2025).

Furthermore, in the context of growing rivalry between the USA and China, pressure on European states to align with one side or the other is mounting. However, the EU strives for a strategic balance, in which it retains the space for autonomous decision-making without completely submitting to the logic of bipolar conflict. This stance is increasingly articulated in terms such as “Geopolitical EU” or “European Sovereignty,” which express the ambition to promote common interests and norms in the global system on the basis of value-anchored multilateralism (Jørgensen et al., 2025).

The European Union today faces a contradictory and simultaneously existential challenge: how to remain a geopolitically relevant actor in a time of growing great power confrontation, escalating security threats, and fragmentation of the international order, all while preserving its own normative identity, internal unity, and democratic values. The pursuit of strategic autonomy is the logical culmination of the recognition that security reliance on external actors, especially the USA, may not be guaranteed in the future. At the same time, the EU acknowledges that it does not possess the traditional instruments of hard power that would enable it to compete effectively with global rivals such as China or Russia (Michaels & Sus, 2024).

This paradox, the ambition for autonomy in the absence of a robust military foundation, conditions the European approach to security and power. Consequently, the EU relies on a combination of soft and civilian instruments, strengthening technological and economic resilience, building network partnerships, and protecting the

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information space. However, these tools are often dispersed, uncoordinated, and limited by divergent national interests. Strategic autonomy thus becomes not only an objective but also a test of the coherence and political will of the European project (Hoeffler et al., 2024; Desmaele, 2025).

Great power rivalry and the weaponisation of interdependence also necessitate a thoughtful and resilient strategy for interaction with the external world—from energy diplomacy and trade regimes to strategic communication. In this context, it is vital for the EU to transition from reactive politics to a proactive geopolitical vision, one that is capable not only of responding to crises but also of co-creating the rules and frameworks of the global order (Varma, 2024).

The current geopolitical reality demonstrates that a post-hegemonic world requires new models of cooperation, where autonomy does not mean isolation but the capacity to act independently while simultaneously cooperating effectively with partners. In this context, the EU can offer an alternative to traditional models of power politics—provided it can transform its normative power, technological potential, and institutional experience into effective strategic operational capability (Taggart & Abraham, 2024; Shkliarevsky, 2024).

4. European Security and the Transformation of Power, Authority, and Competition

Following the analysis of globalised multipolar competition and European strategic autonomy, this section focuses on a deeper reconceptualisation of the fundamental categories of power, authority, and competition in the current security environment.

In the changing global environment, characterised by fragmentation, network interconnectedness, and multipolar rivalry, a fundamental shift is occurring in the understanding of core categories such as power, authority, and competition. These concepts can no longer be considered solely within the context of traditional realism, where power equals military strength, authority equals sovereign legitimacy, and competition equals state dominance in an anarchical system. Instead, they are acquiring new, more complex meanings that reflect the nature of the globalised reality of the 21st century.

Power is now increasingly interpreted not as the ability to compel another actor, but as the capacity to shape the environment in which decision-making takes place, i.e., as 'agenda-setting power' (Barnett & Duvall, 2005). This means that the significance of power is shifting from direct coercive force to structural and normative mechanisms through which actors set the rules of the game. The EU, which possesses limited military capacity but strong regulatory power, is an example of the so-called *market power Europe*, the ability to influence global standards through norms, legal frameworks, and technical regulations (Bradford, 2020).

Concurrently, the understanding of authority is also changing. In an era of transnational challenges that transcend state borders, such as climate change, cyber security, pandemics, or migration crises—authority is increasingly dispersed across multiple levels and actors. The classical principle of state sovereignty is supplemented or replaced by post-sovereign authority, which is based on expertise, multilateral commitments, or technocratic legitimacy (Zürn, 2017). This development leads to the strengthening of the roles of international organisations, agencies, expert networks, and global regulatory regimes.

Even competition itself is no longer solely a matter of military or economic superiority. A new type of competition is emerging: *competitive interdependence*, in which actors are simultaneously partners, rivals, and opponents. In this environment, competition is waged over network positions, access to data, the capacity to shape narratives, and the control of value chains—from critical raw materials to digital platforms. This is competition in a space that is globally interconnected yet simultaneously heavily politicised and geopolitically charged (Farrell & Newman, 2019).

The transformation of the concept of power in international relations reflects profound changes in the conditions under which power is exercised and perceived. While classical realist paradigms emphasised material capabilities, primarily military ones, the contemporary discussion is shifting towards understanding power as a discursive, contextual, and networked phenomenon. In a globalised world, what is decisive is not merely how much power an actor possesses, but how, where, and with what legitimation it is applied.

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In this regard, new types of power, which extend beyond the framework of the classical categories of hard and soft power, acquire crucial significance. These concepts reflect new modalities of influence in a globalised, networked, and information-saturated world, where instruments of coercion are often invisible, indirect, and non-military.

Soft power represents the capacity of a state or actor to influence the behaviour of others through the attractiveness of its values, culture, and political institutions, rather than through coercion or rewards. This type of power is particularly important for the European Union, which has long based its international identity on "normative influence" (Manners, 2002) and the promotion of democracy, the rule of law, and human rights. The EU's soft power manifests primarily in development aid, educational programs, cultural diplomacy, and the capacity to create global regulatory standards (Bradford, 2020).

Sharp power is a newer concept that denotes the manipulative and disinformation techniques of authoritarian regimes, used to undermine public opinion, destabilise democratic processes, and infiltrate the information space of target countries. This is power that is not based on legitimacy or persuasion but on deception, secrecy, coercion, and manipulation. Examples can be found in Russian and Chinese campaigns aimed at spreading propaganda through state-controlled media, infiltration organisations, or online botnets. Sharp power primarily threatens vulnerable segments of society where media literacy or trust in traditional institutions is absent (Walker, 2018; Walker et al., 2020).

Connectivity power, or power through control over connections and infrastructure, represents the capacity to shape and influence global chains—logistical, technological, financial, or communication, that are fundamental to the functioning of the globalised world (Leonard, 2021). This power is demonstrated, for example, in the issue of dependence on semiconductors from Taiwan, access to submarine cables, the dominance of cloud platforms run by American companies, or the influence of China's Belt and Road Initiative. In this context, the European Union realises that without control over critical infrastructure (e.g., 5G networks, digital identities, satellite systems), it cannot be truly strategically autonomous. Connectivity power thus links technological sovereignty with geopolitical standing.

These new forms of power illustrate that contemporary power is increasingly asymmetric, distributed, and less visible than it was in the era of bipolarity. They also show that 21st-century power lies less in holding territory and more in the capacity to shape the flow of information, create narratives, and manage dependencies. For the European Union, this necessitates developing instruments for strategic communication, technological security, and democratic resilience as key pillars of its security and foreign policy.

As follows from the preceding chapters, hybrid threats represent a synthesis of geopolitical rivalry, technological dependence, and narrative competition, manifesting primarily in the grey zone between peace and open conflict. The aforementioned new dimensions of power are therefore crucial, especially in the analysis of hybrid threats, which involve the exploitation of interconnectedness, technological dependence, or social vulnerabilities with the aim of weakening an opponent without direct confrontation. In this sense, hybrid action becomes the "power of the narrative", the capacity to influence what we perceive as true, safe, or dangerous (Rid, 2020; Krishnan, 2024).

Simultaneously, the traditional dichotomy between hard and soft power, which proves analytically insufficient, is being questioned. As Lukes (2021) points out, the most effective form of power is one that operates subtly, without the use of violence, that is, power that shapes preferences, normalises interests, and suppresses alternative options. In this light, current great power strategies increasingly combine economic tools, technological control, narrative dominance, and targeted repressive measures, which demand a new theoretical framework for understanding so-called hybrid power (Cooley & Nexon, 2020; Ivančík & Nečas, 2025).

The concept of authority is also undergoing a crisis and reconfiguration. In the postmodern global order, authority is increasingly distributed among state and non-state actors, with the legitimisation of power bound not only to national sovereignty but also to expertise, representation of interests, and effectiveness of performance. The rise of international regulatory bodies, global platforms (e.g., Big Tech), and scientific

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authorities during crises, such as the COVID-19 pandemic, points to the growing significance of so-called technocratic and post-territorial authority (Zürn, 2017).

This development has serious consequences for the democratic control of power. The shift of authority outside traditional political institutions, especially into the realm of algorithmic governance, cross-border standards, or artificial intelligence, weakens the capacity of citizens to influence decision-making. Therefore, there is an increasing discussion about the need for a re-democratisation of global governance, which would ensure that authority is not merely effective but also accountable and controllable (Deitelhoff & Daase, 2021; Dase et al., 2023).

These theoretical shifts are not merely abstract concepts; they have immediate consequences for political practice and the strategic decision-making of the European Union. The transformation of the concepts of power, authority, and competition has fundamental implications for the strategic thinking of the European Union and its security policy. In an environment where power is increasingly less tied to territory and increasingly interconnected with technology, data, and normative influence, Europe must learn to operate in a "fluid" security space—a space where hybrid instruments intersect with geopolitical ambitions, and where the boundaries between war, peace, and internal and external security are blurring (Helwig & Sinkkonen, 2022; Rosberg, 2025).

For the EU, this means that strategic autonomy cannot be built exclusively on military strength but must include the capacity to define norms, shape narratives, control access to technologies, and protect democratic integrity from external interference. In this sense, autonomy equates to strategic maturity—the capacity to act independently, but not in isolation; the capacity to withstand pressure, but also to co-create the rules of coexistence within the global system (Helwig & Sinkkonen, 2022; Fiott, 2025).

Equally important is that power and authority in the European space are no longer solely a matter for states, but increasingly a matter for networks, platforms, expertise, and transnational actors. It is therefore necessary to fundamentally rethink the security doctrines themselves, which are still based on the assumptions of the Westphalian system. The EU must learn to exercise networked power, a resilient strategy, and reflexive authority that is not only strong but also trustworthy and inclusive (Anghel, 2025; Adriaensen et al., 2025).

Finally, the concept of competition can no longer be reduced to great power rivalry. In an era of globally distributed risks, competition is increasingly a matter of values, reputation, and trust—factors that are advanced not by force, but by a consistent political culture, legitimacy, and the capacity to persuade (Mazzar et al., 2022). In this space, Europe can hold a comparative advantage if it manages to harmonise its value heritage with a pragmatic strategy for linking power, authority, and interests.

Conclusion

The contemporary international reality, shaped by increasing power rivalry, multipolar competition, and strategic uncertainty, presents a fundamental challenge to the traditional understanding of the relationship between politics and security. As this article demonstrates, this is an environment where security can no longer be reduced to the military dimension, nor can politics be limited to the classical instruments of state power. Instead, a profound transformation of the very foundations of the international order is taking place, in which geopolitical interests, technological dependence, normative struggles, and hybrid forms of action intersect.

The analysis showed that globalised multipolar competition changes the logic of security from a defensive framework to a permanent process of strategic rivalry, in which instruments of power are dispersed across military, economic, technological, and informational domains. Concepts such as *weaponised interdependence*, *connectivity power*, and *hybrid power* illustrate that control over connections, norms, and narratives is becoming as important as traditional military capabilities and capacities. In this environment, security becomes a fluid and permanently securitised category, extending into nearly all areas of public policy.

Within this transformation, the European Union finds itself in a particularly ambivalent position. On the one hand, it is exposed to rising pressure stemming from increasing great power rivalry and vulnerabilities arising from asymmetric dependencies; on the other, it seeks to preserve its normative identity based on multilateralism,

the rule of law, and democratic values. The pursuit of strategic autonomy, therefore, is not an isolationist project but a reaction to the realisation that openness without adequate geopolitical capacity can lead to a loss of strategic operational capability.

The article also demonstrated that the concepts of power and authority have undergone a fundamental reconfiguration in recent years. Power is increasingly linked to the capacity to shape rules, standards, and preferences, while authority disperses outside the framework of traditional state sovereignty—into the sphere of expertise, technocratic regimes, and transnational networks. This development significantly complicates the democratic control of power and places new, heightened demands on the legitimisation of political decision-making in the security sphere.

From the European Union's perspective, this means that strategic autonomy cannot be understood exclusively as a matter of building military capabilities and capacities. It is a broader project of strategic maturity that involves the capacity to create and regulate the technological and economic environment, protect the information space, build social resilience, and advance norms within the global system without falling into the logic of purely power-based competition. Autonomy in this sense does not mean separating from the world but the capacity to act independently under conditions of interconnectedness.

Finally, this article contributes to academic discussion by highlighting the need to overcome the binary divisions between hard and soft power, between internal and external security, or between cooperation and competition. European security in the 21st century is being formed in a space where these dichotomies are increasingly less analytically useful. The future relevance of the European Union as a security actor will depend on its ability to integrate values, interests, and new forms of power into a coherent and democratically legitimate strategy for operating under conditions of escalating multipolar competition, great power rivalry, and global uncertainty.

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DEVELOPING STRATEGIES FOR DIGITAL HUMAN RESOURCE MANAGEMENT IN BUSINESS ORGANIZATIONS *

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Abstract. The present research is dedicated to the good practices of using artificial intelligence (AI) in the overall process of digitalization of higher education. The major objective is to identify good practices used so far by the universities in implementation of AI technologies in their everyday life for educational and administrative needs. At the same time, our additional goal is to understand the expectation of students for further implementation of AI in universities. We developed our research in 2 main stages: first one – collection and identification of good practices of universities with AI and digitalization and second one – dedicated to students' expectations. We conducted 25 interviews with representatives of 18 Bulgarian universities, responsible for digitalization. Second one was to provide survey among students (n=254). Our findings reveal that digitalization is defined as one of the leading priorities for universities; the major part of universities have specific strategic document devoted to digitalization. Several challenges are outlined for the smooth digitalization: lack of sufficient resources (including financial, administrative capacity etc.); unwell prepared infrastructure (including lack of common vision for the different systems used so far within the university); emergence of various types of resistance (both in academic and administrative staff) etc. Big advantage for universities using AI is seen in improved quality of the educational process (including introduction of new educational perspectives trough new technologies), improved administrative service, improved public image which is considered to reflect to increased number of potential candidates.

Keywords: digitalization; human resource management (HRM); digital transformation; digital competences; change management; AI

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1. Introduction

Modern business world is inevitably connected and even more precisely – based on digitalization and the development of new technologies. Digitalization covers more and more spheres around us – both of personal and business life – from different forms of communication (social media, chats, platforms) to complex process of data-driven analysis, modeling and forecasting. Digital services are much faster, more reliable, and tailored to consumer current desires and new trends.

Digitization in general can be seen as support from both sides - both from the organization and the employees responsible for the implementation of these processes, as well as from the recipients of digitized services. From an organizational point of view - digital processes, as already mentioned, are faster, more reliable, which leads to improved organizational efficiency (direct optimization of at least the time and human resources re-

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quired for the implementation of the respective process). From the point of view of the respective employee - the digitized process provides much greater opportunities for preventing technical errors, monitoring deadlines, traceability of actions and, respectively, of inactions, etc. At the same time, from the perspective of the recipient of the digital service, the service is delivered quickly and objectively. The digital service maintains consistent quality and speed, regardless of user`s characteristics such as age, sex, financial and social status, gender, religion etc.

Similarly, all human resource management processes align with mainstream practices. At present, digitalization in Human Resources Management could be argued to be relatively widely used in certain processes - such as in the recruitment, but also quite limited in others - such as in employee training and development. At the same time, some imperfections are also observed in the introduction of human resources digitalization, some of which have a more general organizational context, while others are more specific to human resources management. For example, companies often use different systems for various purpose, yet these systems frequently fail to share data with one another. This force employee to enter the same information multiple times across systems, designed for different purposes, making the process inefficient. There are also still organizations that duplicate the digital process with the traditional one, which, on the one hand, does not allow the electronic system to be used to its full extent, while at the same time largely negates the existence of the electronic system at all, since they significantly reduce its efficiency. For example, in many organizations, the organizational culture still requires the submission of a paper leave application, even though the current system used in the same organization for human resources management supports electronic submission.

All of this highlights the need for a holistic approach by senior management to digitalization in human resource management. This article provides just such solutions.

2. Literature review

In recent decades, digitalization has penetrated a wide range of areas of human life - from personal to professional. Human resource management (HRM) is no exception. In this sense, the lively interest of scientific discourse in this specific field of knowledge is quite logical. It should be commented here that during and after the Covid-19 pandemic, digital tools have gained much greater importance and, therefore, much greater interest from a scientific point of view.

According to research of Ulatowska, Wainio and Pierzchała (2023), a great percentage of HRM personnel reported that the organizations they are employed by have adopted digital innovations. The digital innovations include chatbots, dashboards, application software systems, a virtual HRM assistant, and various digital tools (ibid). Schmid et al. (2024) consider that digital transformation alters job functions, introducing new challenges for workforce development and employee careers. In this scenario, the encouragement of creativity via flexible working approaches offers a significant opportunity.

One of the important aspects from organizational digitalization and digital HRM is the change in the leadership. Cheng, Jin and Kwak (2025) admit that digital leadership is crucial in improving organizational sustainability, both directly and indirectly, by fostering digital capabilities and promoting a digital organizational culture. Rialti and Filieri (2024) explore agile leadership in digitalization process of company. They consider that agile leaders facilitate effective digital transformation by implementing rapid decision-making processes, actively engaging in digital initiatives, and adopting both incremental and groundbreaking practices, which contribute to a more streamlined and efficient organization (ibid). Wang, Mansor and Leong (2024) claim that effective digital leadership enhances employees' digital performance by promoting engaged human resource management practices and strengthening their dynamic capabilities.

The impact, that digital practice has on employees and overall performance of enterprise is explored by Zhang et al. (2024). They admit that digital HRM has important role in shaping digital transformation, innovative work behavior, and overall productivity. In this line comes the research of Ogbeibu et al. (2021) who explore the relation between creativity of teams and smart HRM technologies.

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Considering the rapid development with which AI is entering professional life, it is quite logical for scientists to be interested in this direction, especially in the field of HRM. Gupta, Lakhera and Sharma (2024) admit that AI and digital transformation are transforming human resource management practices in multiple sectors. Using AI in recruitment process and its impact on the attractiveness of the organization is the focus on the research, presented by Tursunbayeva et al. (2025). Aguinis, Beltran and Cope (2024) explore how AI, especially ChatGPT could be transformed to a helpful HR assistant. Dimcheva and Stoyanov (2023) assess the role of AI in decision-making process through the managers perceptions. At the same time, Stone, Lukaszewski and Johnson (2024) claim that AI is transforming and will keep transforming how organizations draw in skilled candidates, recruit competent staff, train employees, oversee their performance, and establish compensation and incentive structures. Chowdhury et al (2023) indicate that organizations should extend their focus beyond merely technical resources in adoption of AI in HRM. Authors pointed out that organizations should prioritize the enhancement of non-technical aspects, including human skills and competencies, leadership qualities, team coordination, organizational culture, an innovative mindset, governance strategies, and methods for integrating AI with employees, in order to fully leverage the advantages of AI adoption (ibid).

According to Prikshat et al. (2023), contemporary applications of artificial intelligence have augmented human resources functions. They admit that AI-augmented HRM has taken on a strategic role in achieving outcomes at both the HRM domain level and the organizational level, contributing to a sustainable competitive edge (ibid).

Interesting researches devoted especially for developing digital HRM strategies and future of HRM are proposed by Ruiz et al. (2024), Dabić et al. (2023); Fahey and Saint-Onge (2024). Do, Chu and Shipton (2025) explore AI driven HRM and employee behavior. The authors introduce a framework grounded in self-determination theory. This framework suggests that employee exploration serves as a mediator in the connections between AI-driven human resource management and employee outcomes. Furthermore, trust in artificial intelligence acts as a moderator for these relationships (ibid). Salvadorinho, Ferreira and Teixeira (2024) pay attention on the lean human resource 4.0 with special focus on the possibility of talent management in this organizational environment. Liu (2023) explores the HRM system, based on data mining technology which could be one of the possible future developments of these system. Manroop, Malik and Milner (2024) examine in depth the ethical aspects of using big data in HRM. Andrieux et al. (2024) also explore several important ethical aspects of using generative AI in HRM. Griep et al. (2024) pay attention on the sustainable HRM in a strategic dimension. They outline five key elements of this sustainable development of HRM, namely: long-term thinking; involving employees in decision making process, especially these that affect them; continuously learning and skill development of staff; employee care (which authors claim as very important aspect for achieving sustainable HRM) and organizational system and structure that are in line with the HRM principles. In this regard Mamun et al. (2024) consider the socially responsible HRM could achieve sustainable performance of the company.

At the same time, scholars are concerned about some aspects of comprehensive digitalization in managing human resources, especially connected to controversial practices such as using Algorithmic Management and Algorithmic control over employees. Lukaszewski and Stone (2024) examine the possibility if AI and machine learning (ML) could breach ethical norms. Scholars assess how AI and ML models influence perceptions regarding privacy invasion, biases and unjust discrimination in hiring processes, and the potential damage to individuals and organizations stemming from inaccurate data produced by AI and ML. They develop and propose strategies that organizations could implement to address these significant ethical challenges. Breidbach (2024) also admits that in spite of numerous advantages, algorithmic decision making carries an intrinsic downside that can lead to problems such as diminished privacy for individuals and an imbalance of power within society. Meijerink and Bondarouk (2023) consider that algorithmic input, processes, and outputs enable employers to exert control over employees, consequently reducing both job autonomy and the perceived value of work for these individuals. Scholars highlight that the nature of algorithmic management is complex and essentially - dual; while it restricts job autonomy and value, it also has the potential to enhance both for workers through HRM algorithms (ibid). Bujold, Parent-Rocheleau and Gaudet (2022) explore the opacity of using algorithmic management. Their findings indicate that the clarity of algorithmic surveillance

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correlates positively with procedural justice, while the clarity of algorithmic performance management is positively associated with distributive justice. Several studies also could be pointed out in this line: Deng et al. (2024), Trautwein et al. (2025), Zhou, Wang and Chen (2023). Cheng and Hackett (2021) admit that although the algorithms used in Human Resource Management (HRM) are generally not rooted in robust theoretical frameworks, the term "black box," commonly used by critics to describe these algorithms, may not be entirely fitting. Rather, it is more accurate to define HRM-related algorithms as heuristic methods.

In Bulgarian context several interesting researches have to be outlined, when we consider HRM, digital development and change management. Kostev and Anguelov (2024) explore the perceptions of employees in public administration towards overall digital transformation in organizations. Ilieva, Anguelov and Nikolov (2019) propose a structured way in which an organization can become more agile and respond more quickly to change. At the same time research shows that sustainable human capital development and good working conditions increase employee engagement and highlight the need for wider implementation of digital solutions in human resources management (Anguelov, 2019).

3. Methodology of the research

This article in fact represents a final result from a two years lasting project, financed by the University of National and World Economy in Sofia, Bulgaria. During the implementation of the project, various tools were developed, through which primary information was collected from numerous representatives of stakeholders - employees in companies, HR managers and experts, senior management, business owners, in order to assess the different views and perspectives on attitudes, stereotypes and prejudices about the digitalization of processes and activities related to human resource management.

This study uses a mixed-method design, combining quantitative and qualitative methods, to provide both a broad range of data on organizations' attitudes and readiness for digitalization in human resource management, as well as a deeper understanding of the strategies and challenges they face.

The choice of a mixed research method was a logical solution, since the topic of digitalization in human resource management has both quantitative and highly qualitative dimensions. Information was needed that would show the general trends in attitudes towards digital solutions, but also a deeper understanding of the reasons behind these attitudes. Quantitative data provides clarity about the degree of readiness of organizations, the actual use of technologies and the existing barriers. Qualitative data, on the other hand, reveals how people perceive these changes, what fears or expectations they have and how the organizational environment influences the process. Therefore, in the project, both approaches were used in parallel, with the aim of achieving mutual complementarity and providing richer primary material necessary for the subsequent analysis and interpretation of the results.

The choice of a mixed research method was one of the logical options for a scientific approach and solution, since the topic of digitalization in human resource management has not only quantitative, but also highly qualitative dimensions. It was necessary to collect primary information that would show the general trends in attitudes towards digital solutions. At the same time, however, it was equally necessary to achieve a deeper understanding of the reasons behind these attitudes. Quantitative data provides clarity on the degree of readiness of organizations, the actual use of technologies and the existing barriers. Qualitative data, in turn, reveals how people perceive these changes, what fears or expectations they have and how the organizational environment influences the process. Therefore, the project used both approaches in parallel, purposefully using the synergistic effect of the mutual complementarity of these approaches. The different steps within the methodology is presented in Figure 1.

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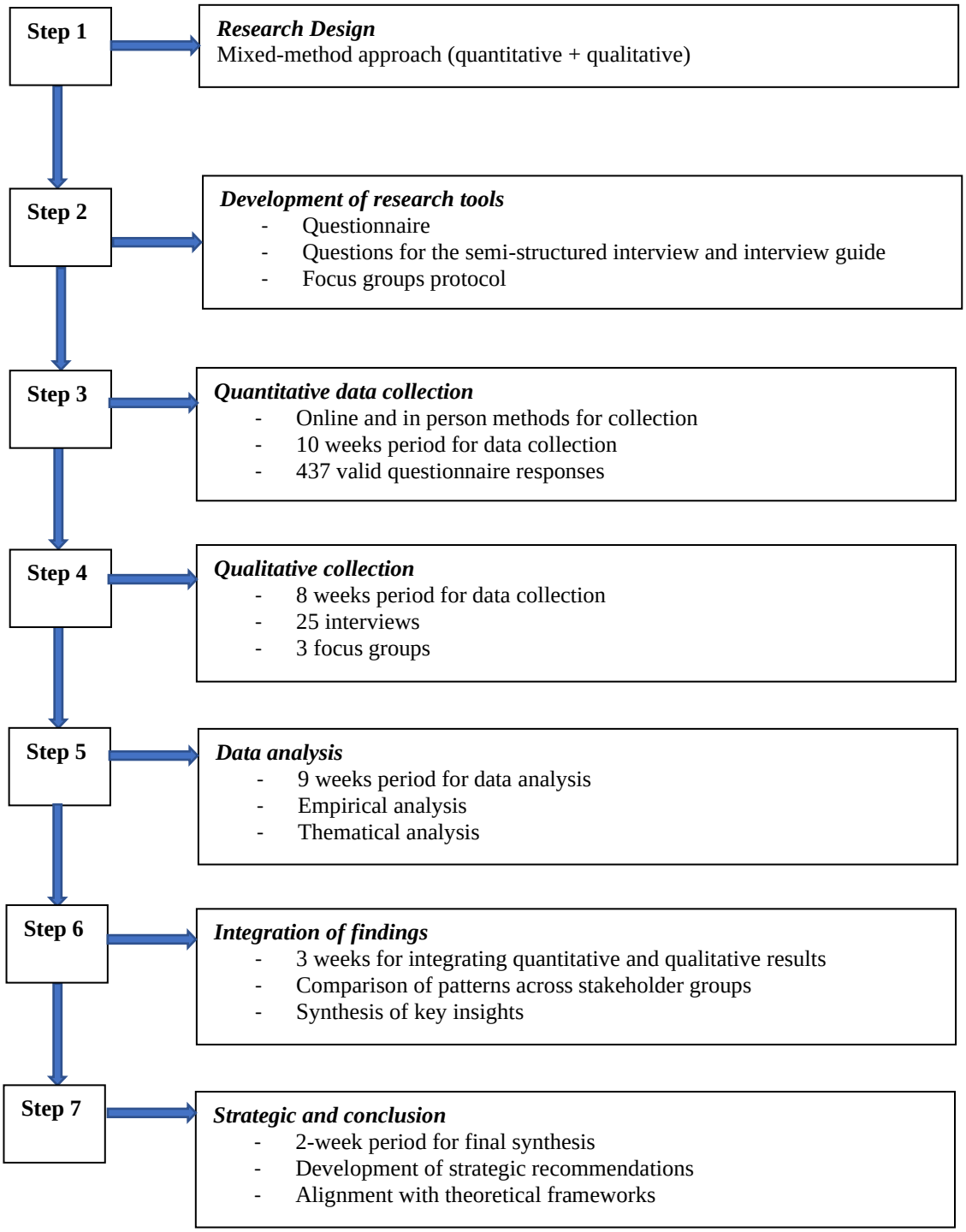


Figure 1. Complete research methodology: stages, instruments, and procedures

The quantitative part of the study collected 437 valid questionnaire responses. The sample included 257 employees, 113 HR specialists, 46 middle managers and 21 owners or representatives of senior management. The specially developed survey contained 42 questions, structured in five thematic blocks: level of digitalization, attitudes towards digital HR tools, perceived benefits and risks, competencies and training, organizational culture and readiness for change. The surveys were distributed both online and on paper to organizations from 12 different economic sectors, including services, trade, manufacturing, IT, healthcare and public administra-

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tion. The sample included micro-, small, medium-sized and large enterprises, which allowed for the analysis of possible differences according to organizational scale.

To achieve the objectives of this study, we used several composite indices that were constructed by combining variables that are thematically related. These variables were assessed using a 5-point Likert scale. From this perspective: the index for the degree of digitalization of HR processes in a business organization consists of the following sub-elements, assessed by the degree of use of: electronic systems for selecting employees, automated administrative processes, etc. In turn, the index for attitudes towards the use of digital HR tools combined statements, assessed by degree, related to the level of perceived usefulness, the added value of convenience for employees, the assessment of the level of effectiveness and readiness for use. At the same time, to assess the internal consistency of each composite, the Cronbach's α coefficient was used, which measures the degree to which the elements in a given scale reflect the same latent construct. The α values were calculated by analyzing the correlation matrix between the individual items of the index. Values above $\alpha > 0.70$ are considered an indicator of good reliability of the scale. In the present study, all indices used meet this threshold, which allows their subsequent use in the analysis.

The qualitative part of the study included 25 semi-structured interviews and three focus groups, each with 6 to 8 participants. The interviews were conducted with HR managers, HR experts, department heads and senior management representatives. The average duration of each interview was between 45 and 60 minutes. The interviews focused on the strategic aspects of digitalization, experiences with implementing HR technologies, barriers to transformation and subjective attitudes towards change. Focus groups were conducted with employees from different departments and provided data on daily practices, concrete examples of using digital tools and the dynamics of organizational attitudes. All interviews and group discussions were recorded, transcribed and analyzed through thematic coding.

Several important steps were taken to increase the reliability and validity of the study. The survey questionnaires and interview questions were pilot tested with a small group of participants to check the clarity of the wording and logic of the questions. Data from the different groups of participants were triangulated to compare the results and identify similarities and differences between employees, HR professionals and managers. The analysis included a comparison between organizations of different sizes and sectors, which contributed to a broader generalization of trends. Within the qualitative analysis, some of the participants were given the opportunity to confirm or comment on preliminary interpretations (member-checking), which added additional credibility.

The main objective of the study is to identify and justify the most effective strategies for digitalization in human resource management, by analyzing the main factors that support or hinder their successful implementation in organizations.

For the purposes of the study, the following hypotheses were developed:
Hypothesis 1 (H1): Employees working in organizations with a higher degree of digitalization of HR processes demonstrate more positive attitudes towards the use of digital HR tools.
Quantitative data (437 surveys) allow for the measurement of both attitudes and the degree of digitalization. The analysis of the data collected from the empirical study can confirm or reject this hypothesis. At the same time, the qualitative interviews complement the understanding by clarifying the reasons - for example, previous experience, organizational culture, level of education.

Hypothesis 2 (H2): HR professionals show a higher readiness to adopt digital HR solutions compared to employees who do not work in units performing HR functions.
The 113 HR professionals and 257 employees surveyed allow for comparison between groups. At the same time, qualitative interviews allow for interpretation of differences – for example, knowledge of the benefits, better access to training or a greater role in the implementation processes.

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Hypothesis 3 (H3): Negative stereotypes and prejudices towards digitalization are more prevalent in organizations with low cultural and organizational readiness for change.
The survey results allow for the measurement of attitudes, stereotypes and organizational readiness. Qualitative data helps to determine which aspects of culture generate resistance. Focus groups add real examples and context for these stereotypes.

Hypothesis 4 (H4): Organizations that invest in training and digital competencies achieve more successful implementation of HR technologies.
The quantitative instrument contains questions about training, digital skills and actual use of technology. The interviews clarify what types of training are effective in this direction, where there are gaps and what is considered success. Thus, the mixed method approach provides both evidence and explanations.

Hypothesis 5 (H5): Organizations in which senior management is actively involved in the processes of digitalization of HR activities achieve a higher degree of actual implementation and use of digital HR tools.
The surveys measure both the degree of participation of management and the actual use of HR technologies, which allows for verification of the relationship. In turn, the interviews provide context for how and in what form this management support is implemented (for example, through resourcing, prioritization or the creation of internal change teams). Thus, the mixed method allows for capturing both the dependence and the mechanism behind it.

Hypothesis 6 (H6): There is a significant difference in attitudes towards digitalization between smaller and larger organizations.
The sample includes enterprises of different sizes. The quantitative part allows for statistical comparison by organizational scale. The qualitative part shows the reasons – for example, lack of resources, different priorities or different organizational structure.

4. Surveys Results

Sample description
The questionnaire was distributed both online and in person with representatives of the target groups. As a result, a total of 437 valid responses were received. The sample is structured as follows: 257 associates – in expert positions, 113 HRM specialists, 46 middle management managers, as well as 21 owners or top managers of companies. Such a diversity of representatives in the sample helps to capture the different points of view on the digitalization of HRM.

The respondents represent business and public organizations operating in 12 different sectors of the economy, including trade, services, manufacturing, IT, healthcare and others. At the same time, the study purposefully included companies of different sizes – from micro enterprises to large corporations operating on several continents. In this way, it is possible to analyze whether there is a relationship between the attitude towards digital technologies, especially in HRM, and the size of the company or the type of economic sector and the type of work.

In addition, 25 semi-structured interviews were conducted in face-to-face meetings with HR managers, experts, and team leaders. The average duration of the interviews was about 60 minutes, with the aim of gaining greater clarity and depth in how companies introduce new technologies and what difficulties they face in planning and implementing the change.

Three focus groups were also conducted with 6–8 participants each. The selection of participants in these focus groups was precise and included both representatives of HR departments and other specialists, as well as middle-level managers. The aim was to track the real, unspoken expectations of employees and management regarding the digitalization of HRM, the related stereotypes and attitudes, prejudices, fears, and expectations.

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Quantitative Results

(H1): Employees working in organizations with a higher degree of digitalization of HR processes demonstrate more positive attitudes towards the use of digital HR tools.

To test this hypothesis, we used two main indicators from the survey. First, it was the degree of digitalization of HR processes, which was established by means of a composite index consisting of several elements such as: degree of use of online personnel selection systems, electronic forms for performance appraisal, automated administrative processes, including automated management decision-making related to career growth, providing incentives for well-done work or imposing penalties for non-performance. Second, were attitudes towards digital HR tools, which were measured by means of a complex assessment scale, encompassing statements about usefulness, convenience, efficiency and readiness for use. Both indicators showed good internal consistency ($\alpha > 0.70$), which allowed them to be used in the subsequent analysis.

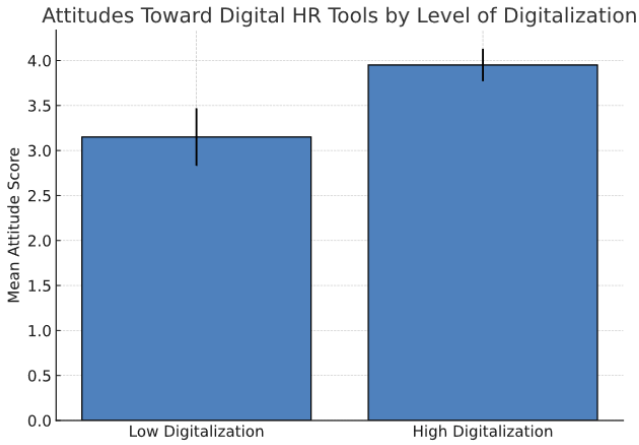


Figure 2. Attitudes toward digital HR tools as a function of organizational HR digitalization (H1).

Figure 2 compares the average attitudes towards digital HR tools in two groups of organizations classified according to the degree of digitalization of their HR processes – those with low digitalization and those with high digitalization. The vertical axis shows the average score from the composite attitude index formed on the basis of a Likert scale (e.g., from "strongly disagree" to "strongly agree"). The horizontal axis shows the two groups of organizations.

The results show a clear difference between the groups. The situation for organizations with low digitalization is the average attitude score of around 3.15. In reality, this reflects the much more moderate or, in other words, hesitant attitude of employees towards digital HR solutions. This result may be due to the lack of sufficient experience in using such digital tools, lack of practical conviction about the effects that such tools would have on the organizational climate and/or a direct lack of confidence in their usefulness.

In parallel, employees in organizations characterized by a high degree of digitalization show visibly more positive attitudes, with an average value of around 3.95. This indicates a better attitude towards the adoption of digital technologies in HR processes. This may be due to their better knowledge, including in terms of the benefits that such technologies bring, the completion of specialized training to work with such tools, clearer processes or personal positive experience from their exploitation.

The vertical error bars (Figure 2) depict the standard error of the mean, which allows us to assess the stability of the results within each group. The greater length of the error bar in the low digitalization group indicates greater variability in employee attitudes – that is, opinions are more heterogeneous. In the high digitalization group, the error is smaller, which suggests greater similarity in assessments and a more stable positive attitude.

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Figure 2 visually confirms the trend identified in the quantitative analysis: the higher the degree of digitalization of HR processes, the more positive the attitudes towards the use of digital HR tools. The level of technological maturity of the organization, as well as the technological environment, have a significant impact on the perceptions and attitudes of employees.

Hypothesis 2 (H2): HR professionals show a higher readiness to adopt digital HR solutions compared to employees who do not work in units performing HR functions.

To confirm or reject this hypothesis, we used two main types of indicators. The first refers to the professional role of the survey participants. The respondents were divided into two main categories – the first of them are HR specialists (n = 113), and the second was formed by experts who do not work in units performing HR functions (n = 257). The second main indicator refers to the readiness that employees show regarding the adoption of digital HR solutions. We establish it through a scale that includes various statements about the desire to use digital tools, including expected usefulness from using digital solutions, as well as confidence in one's own knowledge and skills in handling such digital tools, as well as attitudes towards the introduction of new digital solutions. The scale showed good internal consistency ($\alpha > 0.75$), which allows a reliable comparison between the two groups.

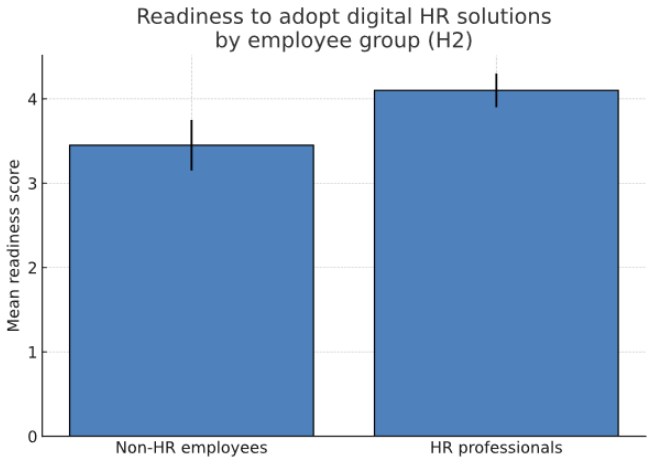


Figure 3. Mean readiness to adopt digital HR solutions among non-HR employees and HR professionals (H2).

Figure 3 presents a comparison of the average values indicating the readiness to adopt digital HR solutions by the two main groups of participants – experts who do not work in human resources departments (Non-HR employees) and HR professionals themselves (HR professionals). The vertical axis shows the average value of the readiness index. It is determined according to answers to a series of statements assessed using a Likert scale. The horizontal axis presents the two compared groups. As can be seen from the graph, the results show a relatively clear difference between the two main categories of participants. The average readiness score among employees who do not professionally deal with HR functions is approximately 3.45. This result can be interpreted as a more moderate attitude on their part towards the use of new digital HR tools. This value also suggests a certain caution, which is most likely due to the relatively rare interaction with such technologies, as well as more limited awareness of their capabilities. At the same time, it may also be due to expectations for changes that are not sufficiently well communicated at the organizational level.

In contrast, HR specialists show a relatively higher level of readiness, with an average value of around 4.10. This demonstrates a more clearly expressed positive attitude towards the introduction and use of digital HR solutions. The higher result can be explained by professional knowledge of tools such as information systems and their real effectiveness, by the use of electronic recruitment platforms, performance appraisal systems and making management decisions based on systematic data analysis provided by such digital systems. It is also possible that HR specialists have higher digital competence specifically in the field of HR tools, which con-

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tributes to a more confident attitude towards the new opportunities that technologies provide, including in the field of HRM.

The vertical error bars represent the standard error of the mean (see Figure 3), which provides information about the variation of the scores within each group. The longer error bars for employees outside HR roles indicate a greater diversity in their attitudes – in this group, opinions range from more positive to more reserved. In the HR professionals' group, the error bars are shorter, suggesting greater consistency of assessments and a more sustained positive attitude towards digital HR solutions. The graph clearly visualizes the trend also established through the analyses of the empirical data: HR professionals demonstrate a higher readiness to adopt digital HR tools compared to employees who do not work in HR units. This conclusion supports Hypothesis 2 and confirms that professional role has a significant impact on attitudes towards digitalization in the field of human resource management.

Hypothesis 3 (H3): Negative stereotypes and prejudices towards digitalization are more prevalent in organizations with low cultural and organizational readiness for change.

We relied on two main indicators to be able to test this hypothesis – to confirm or reject it. The first indicator is about cultural and organizational readiness for change. From this perspective, respondents were grouped into two categories based on a composite index: organizations with low readiness for change and organizations with high readiness for change. The index consisted of a series of statements related to openness and readiness to introduce and adopt innovations, flexibility and adaptability of work processes, support from management and perceived level of change by employees. The scale showed high internal consistency ($\alpha > 0.80$), which allows for reliable classification of organizations. The second indicator measures the presence and intensity of negative stereotypes and prejudices towards digitalization in terms of specific HRM processes. It consisted of statements that tested employees' concerns about fears related to excessive control and automation of the measured performance of each employee, fears related to loss of autonomy and even to some extent infringement of basic human rights (e.g., related to excessive control), loss or retreat of people from management decision-making at the expense of algorithms, doubts about the reliability of digital tools, and concerns related to excessive complexity. This scale also showed good internal consistency ($\alpha > 0.78$).

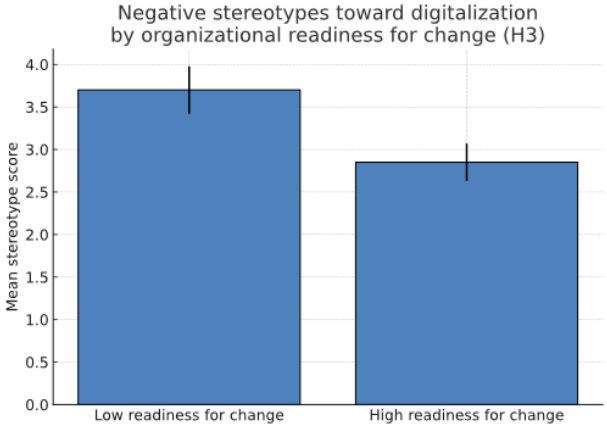


Figure 4. Evaluation on the remote assessment effectiveness, in %

Figure 4 presents a comparison of the mean values of negative stereotypes and prejudices towards digitalization between two groups of organizations classified according to their cultural and organizational readiness for change. The vertical axis shows the mean value of the negative stereotype index, formed using a Likert scale. The horizontal axis shows the two studied groups: organizations with low readiness for change and organizations with high readiness for change.

The results show a clear difference between the groups. In organizations with low readiness for change, the mean value of negative stereotypes is approximately 3.70, which indicates more pronounced reservations and

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concerns about digital technologies. This higher value can be explained by a more conservative organizational culture, weaker or directly ineffective communication about technological changes, as well as previous unsuccessful attempts to implement digital solutions in various processes in the organization. In contrast, organizations with high readiness for change demonstrate a significantly lower mean value — around 2.85. This clearly shows a more positive, constructive and open-minded attitude towards digitalization in HRM, higher trust in technological processes in general and in the field of HRM in particular, as well as a more positive assessment of the benefits that their implementation can bring to the organization.

The vertical error bars represent the standard error of the mean (see Figure 4), through which the stability of the results is assessed. It is noticeable that the error bar in the low readiness group is longer, which indicates greater variability and diversity in attitudes. This means that in these organizations there is a mixed picture - some employees show moderate reservations, while others express a strongly negative attitude. In the high readiness group, the error bars are shorter, which should be explained by their more unified and relatively clearly expressed positive attitude towards digitalization.

Figure 4 clearly visualizes the trend established by statistical tests: negative stereotypes are significantly more pronounced in organizations with low readiness for change, which supports Hypothesis 3. This reasonably leads to the conclusion that the role of organizational culture is decisive for the overall readiness of employees for change, including the successful adoption of digital technologies in the field of HRM for the needs of the respective organization.

Hypothesis 4 (H4): Organizations that invest in training and digital competencies achieve more successful implementation of HR technologies.

To establish the validity or reject this hypothesis, two main indicators were used. The first indicator is the degree of investment in training and development of digital competencies of employees in organizations. It was measured using a composite scale that included various elements such as: frequency of training, types of training provided (technical, software, process), access to training organized for the needs of the organization (internal) or to external training organized by specialized training organizations; availability of comprehensive programs for improving digital skills. The composite scale also included the subjective assessment of employees about the attitude and support from the organization and management for the overall development of digital capabilities. The scale showed high internal consistency ($\alpha > 0.82$). The second indicator measures the success of the implementation of HR technologies. It was established using indicators such as: degree of actual use of the implemented tools, level of employee satisfaction with digital HR systems, ensuring a smooth transition in the transformation and transition from traditional to digital processes, as well as the level of perceived efficiency, benefit and added value of new technologies. This scale also demonstrates good reliability ($\alpha > 0.80$). For the purposes of the analysis, organizations were divided into two groups according to the level of investment in training: organizations with low investment and organizations with high investment.

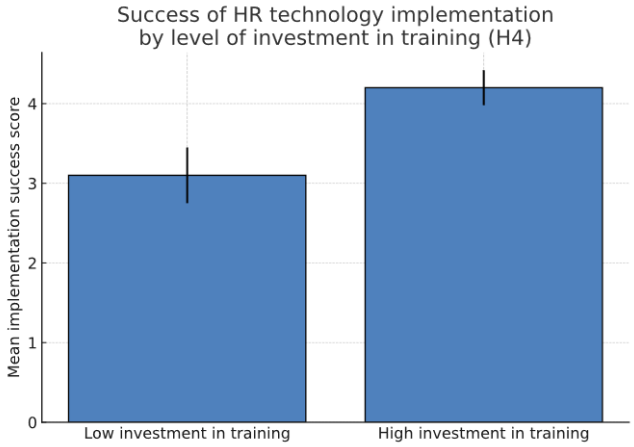


Figure 5. Success of HR technology implementation by level of investment in training (H4)

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Figure 5 compares the average success rates of HR technology implementation in two groups of organizations, determined by the level of investment in training and development of their employees for the purposeful deepening of their digital competencies. The vertical axis shows the average value of the implementation success index, which is based on Likert scale ratings. The horizontal axis shows the two main groups – organizations with low investment in training and organizations with high investment in training. As can be seen from the graph, organizations with low investment in training and development of digital competencies of employees reach an average success index value of around 3.10. This indicates a much more limited success rate in implementing HR technologies, which in turn includes a lower degree of actual use of the systems, more frequent experience of difficulties in working with them and relatively more moderate employee satisfaction. The longer error bar in this group also shows greater variability in the estimates – in some organizations the implementation is more successful, but in others it encounters serious difficulties, which indicates an unstable and heterogeneous process.

In the group of organizations with high investments in training, the average value of the success index reaches approximately 4.20. This result, in turn, can be interpreted as achieving significantly better results in the digital transformation in the field of HR. In these organizations, digital tools are used more actively and systematically, employees declare higher satisfaction with working with them, and the transition from traditional to digital processes is assessed as smoother and more managed. The error bars here are shorter, which indicates greater consistency of the estimates and a more stable positive perception of the implemented technologies.

The vertical error bars represent the standard error of the mean (Figure 5), which allows us to assess the stability of the results within each group. The longer error bars for low-investment organizations indicate a wider range of estimates and a stronger dependence on the specific context, while the shorter error bars for high-investment organizations indicate a more uniform perception of the benefits of training and technology. The graph clearly shows the trend also established by the analysis of the empirical data: organizations that invest purposefully in training and development of digital competencies achieve more successful implementation of HR technologies. Thus, Figure 5 provides strong and clear support for the validation of Hypothesis 4. In this way, the role and importance of training as one of the main elements for a successful digital transformation in human resources management becomes extremely clear.

Hypothesis 5 (H5): Organizations in which senior management is actively involved in the processes of digitalization of HR activities achieve a higher degree of actual implementation and use of digital HR tools.

To test the validity of this hypothesis, we again used two main indicators. The first one measures the activity and commitment of senior management in digitalization processes. This indicator is also based on a composite index assessment, including statements about: providing strategic support from senior management for the overall digital transformation process, active participation of management in planning and decision-making in this process, systematic and targeted provision of resources for technology implementation, active participation in communication related to clearly explaining the goals of digital transformation, as well as the presence of clearly expressed leadership encouraging innovation. The scale showed high internal consistency ($\alpha > 0.85$).

The second indicator measures the degree of actual implementation and use of digital HR tools. It includes elements such as: the frequency of use of HRIS systems in the organization, the use of systems in electronic selection of new employees, making decisions about online training, electronic platforms for managing and evaluating the performance of employees, automation of administrative processes and integration of systems for analyzing HR data. The scale demonstrates good reliability ($\alpha > 0.80$).

For the purposes of the analysis, the organizations were divided into two groups: organizations with low involvement of senior management and organizations with high involvement of senior management.

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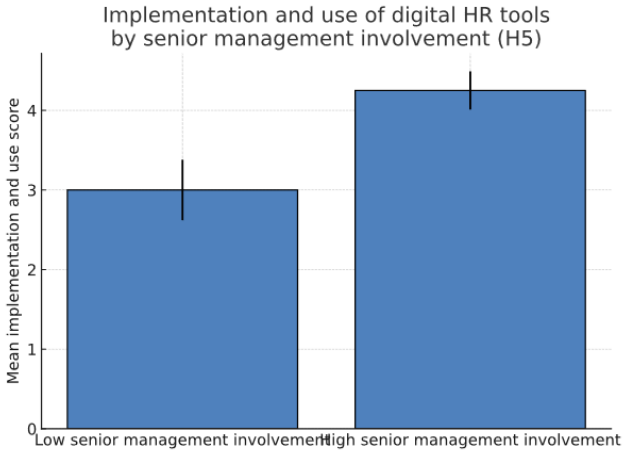


Figure 6. Mean level of implementation and use of digital HR tools in organizations with low and high senior management involvement (H5)

Figure 6 above compares the average values of the degree of actual implementation and use of digital HR tools in two groups of organizations, which are in turn determined by the level of engagement of senior management in digitalization processes. The vertical axis shows the average value of the index for implementation and use of digital HR tools, formed on the basis of a Likert scale. The horizontal axis shows the two compared groups: organizations with low engagement of senior management and organizations with high engagement of senior management.

In organizations where senior management is not engaged in the digitalization processes of HRM, the average value of the index is approximately 3.00. This result indicates a relatively limited and less systematic use of digital HR tools. In organizations of this type, digital solutions often remain at the level of partial implementations, being used only by certain departments or applied in a limited number of HR processes. The vertical error bar in this group is relatively longer, which indicates greater variability in the estimates. This could lead to the conclusion that the degree of implementation is very heterogeneous between individual organizations, as well as between the units within these organizations themselves - in some of them digitalization is developing more successfully, while in others it is almost absent.

In contrast, organizations with high senior management commitment show a significantly higher average value - around 4.25. This value reflects a larger-scale, more strategically consistent and sustainable implementation of digital HR tools. In these cases, digital solutions are integrated into core HR practices, testifying to their active use in daily work. At the same time, the implementation itself is supported by resources, clear communication and strategic visionary planning. The error bar for this group is shorter, which means lower variability and more stable estimates within different organizations. This is an indicator of a coherent and more successful digitalization process.

The vertical error bars represent the standard error of the mean (Figure 6), which provides important information about the reliability of the estimates. The longer error line in low-engagement organizations highlights the instability and inconsistency of processes. At the same time, the shorter error line in high-engagement organizations shows that digitalization is implemented much more evenly there. The visual results clearly confirm the empirical trend established through the analysis of the empirical data, from which the unambiguous conclusion follows that the active engagement of senior management is extremely important for a higher degree of real implementation and use of digital HR tools. Figure 6 directly supports Hypothesis 5, emphasizing the importance of leadership as a driver of successful digital transformation.

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Hypothesis 6 (H6): There is a significant difference in attitudes towards digitalization between smaller and larger organizations.

To test this hypothesis, we used two main indicators. The first one is related to the size of the organization, based on the number of employees employed in it. For the purposes of this analysis, organizations were classified into two categories: small organizations – those with up to 50 employees and large organizations – with over 250 employees. This categorization is in accordance with generally accepted criteria in management and organizational research, as well as in accordance with applicable European legislation in this area. The second indicator is the attitude towards digitalization itself, measured by a multi-component scale, including statements about the perceived usefulness of digital HR tools, their convenience in use, expected effect on process efficiency, trust in technologies and readiness to work with modern digital solutions. The scale showed excellent internal consistency ($\alpha > 0.86$).

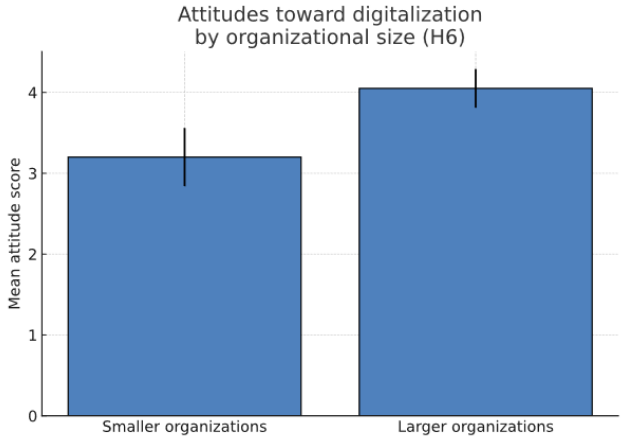


Figure 7. Mean attitudes toward digitalization in smaller and larger organizations (H6)

Figure 7 presents a comparison of the average values of attitudes towards digitalization between smaller and larger organizations. The vertical axis shows the average value of the attitude index towards digitalization, formed on the basis of a series of statements rated on a Likert scale. The horizontal axis shows the two groups: Smaller organizations and Larger organizations. The average value of the attitude index towards digitalization in smaller organizations is approximately 3.20. This value is indicative of a slightly positive, but at the same time rather cautious attitude towards digital solutions. Such organizations are often characterized by relatively serious limitations in terms of resources, technological infrastructure and personnel. This, in turn, reflects greater caution, including hesitation when introducing new digital tools. The vertical error bar for this group is relatively longer, which indicates greater variability in assessments – some employees are more open to digitalization, while others remain more reserved.

In larger organizations, the average value of the same index is significantly higher — around 4.05. This indicates more clearly expressed positive attitudes towards digitalization. In these organizations, digital technologies are more often integrated into the main processes, there is a more developed IT infrastructure, and employees more often have experience with various digital systems, including in the field of human resources management. The error bar in large organizations is shorter, which indicates lower variability and a more stable positive attitude among employees. The vertical error bars represent the standard error of the mean, allowing to assess the stability and reliability of the estimates. The larger range in smaller organizations suggests that in them the processes of digital transformation are more heterogeneous, while in larger organizations the attitudes are more consolidated.

Figure 7 clearly presents the trend established by the quantitative analysis: attitudes towards digitalization are more positive in larger organizations than in smaller ones. This supports Hypothesis 6 and highlights the importance of organizational size and related technological maturity as factors directly influencing the adoption of digital transformation.

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Qualitative Results

The qualitative component of the study aims to build on the quantitative results by providing a deeper understanding of the mechanisms behind the attitudes and behaviors of different groups of participants regarding the digitalization of HR activities. For this purpose, data from 25 semi-structured interviews and 3 focus groups conducted with employees, HR professionals and management representatives from organizations of different sizes and sectors were used. The analysis of the qualitative data was conducted through thematic analysis, which allows for the systematic identification, grouping and interpretation of recurring patterns and meaning in the participants' statements.

During the analysis, three main themes were outlined that most clearly describe the attitudes and experiences of the participants regarding digitalization:
1. Perceived benefits of digitalization – includes descriptions of specific advantages, increased efficiency and improved process management.
2. Barriers and challenges – focused on the lack of skills, resistance to change, technical difficulties and organizational constraints.
3. The role of management and organizational culture – reflecting the ways in which leadership, communication and support from management shape attitudes towards digitalization.

Each of these themes includes several subcategories that describe in more detail the observed patterns in the data. They are illustrated with selected quotes that allow the logic and argumentation of the participants to be followed. The qualitative results are presented in a way that first complements the justification of the quantitative trends; provides a deeper understanding of the processes behind the hypotheses; reveals the contextual factors that influence attitudes, behavior and actual use of digital HR tools.

Theme 1: Perceived benefits of digitalization

The first theme that stands out in the analysis of the interviews and focus groups is the perceived benefits of the digitalization of HR processes. These benefits manifest themselves in several very clearly defined areas. It is striking that they are largely shared by participants in different roles and by representatives of organizations of different sizes. However, HR specialists and employees from large organizations demonstrate a higher awareness of the strategic advantages of digitalization, while participants from small organizations emphasize more operational and immediate conveniences.

Subcategory: Increased efficiency and time savings

One of the most frequently cited benefits is related to the reduction of administrative burden and optimization of time. Participants share that digital tools significantly speed up work and allow for faster processing of requests, documents and inquiries. These statements are particularly strongly expressed among HR specialists.
"*Automation frees us from hours of routine work. We used to keep everything in spreadsheets, now the system does it all by itself.*" (HR manager, large organization)
"*Even just electronic leave requests have saved us a lot of time. We don't run around the rooms for signatures.*" (employee, small company)
This subcategory qualitatively explains the higher quantitative scores in the groups with higher digital maturity.

Subcategory: Improved transparency and traceability of processes

Many participants emphasize that digital HR platforms allow for clear tracking of processes and actions — from requesting leave to evaluating performance. This creates a sense of greater fairness and consistency.
"*The system provides visibility – we all see the same thing. This eliminates a lot of misunderstandings.*" (employee, large organization)
Transparency is perceived as a very important element in creating trust in systems, especially among employees who previously distrusted traditional procedures.

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Subcategory: Better decision-making through access to data
One of the most distinct benefits cited by HR representatives is the ability to work with up-to-date and reliable data, which facilitates analysis.
"*We have real-time data. Decisions for training, assessments, selection – everything is now supported by evidence, not intuition.*" (HR business partner)
This subcategory supports the quantitative results in H1 and H2, which show a higher positive attitude in digitally advanced organizations.

Subcategory: Improved employee experience
Participants from all groups share that digitalization makes everyday tasks easier – submitting requests, communicating with HR, accessing documents and information. This improves the overall experience in the organization, especially for employees who actively use online platforms.
"*When everything is on the phone, it's just easier. You don't depend on the workplace, on papers, on HR.*" (employee, large IT company)
These subcategories clearly show that the perceived benefits of digitalization are in fact multi-layered and affect both the individual experience of employees and strategic business processes. Theme 1 supports the trends observed in the quantitative analysis — especially the differences between HR professionals and employees outside the HR function (H2), as well as between small and large organizations (H6). It reveals the reasons for the more positive attitudes in organizations with a higher level of digitalization and a more developed technological environment.

Theme 2: Barriers and challenges to digitalization
The second theme, extracted from the qualitative content, is related to the main barriers and difficulties that organizations encounter when implementing and using digital HR tools. These obstacles manifest themselves both at the individual and organizational level. They are the basis for explaining the lower quantitative values in smaller, less digitally mature or culturally unprepared organizations. Several subcategories stand out in the analysis, describing the main difficulties.

Subcategory: Lack of sufficient digital skills and the resulting insecurity
One of the most common barriers, especially among employees who do not work in HR, is the lack of sufficient digital competencies or confidence in their own abilities. Participants emphasize that uncertainty when working with new technologies often creates stress.
"*I am afraid of making a mistake. We are not properly trained and this stops us.*" (employee, focus group)
"*Some colleagues want to work the old way because they feel more secure.*" (employee, small company)
This subcategory explains the differences observed in quantitative results between HR and non-HR employees (H2), as well as the lower adoption of digitalization in small organizations (H6).

Subcategory: Resistance to change
Resistance to change is the second main barrier. Some participants perceive digitalization as a threat to the established way of working, have concerns about the level and quality of control, especially in terms of assessing task performance, or as an additional burden. This resistance is not always overt; it often manifests itself in passive postponement or neglect of new systems.
"*We have people who say: 'I don't see why we should change something that works.' It slows us down a lot.*" (HR professional)
"*To be honest, for me it was unnecessary complications. I'm used to doing things differently.*" (employee, large organization)
This barrier is particularly pronounced in organizations with low cultural readiness for change, supporting the quantitative trends in H3.

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Subcategory: Lack of resources and capacity
Representatives of small organizations share that limited financial and human resources hinder the implementation of modern HR technologies. There is often a lack of sufficient financial resources, sufficient time for training or technical support.
"*With us, it's all about money and time. We have the desire, but we don't have the capacity to maintain such systems.*" (small company owner)
Resource limitations are one of the leading reasons for lower attitudes towards digitalization in small organizations (H6).

Subcategory: Technical difficulties and usability issues
Participants from various sectors emphasize that some digital tools are too complex, with a difficult-to-understand user interface or insufficiently good functionality. Technical difficulties often increase resistance and reduce trust in digitalization.
"*The system is not intuitive. You have to press five buttons for something very basic.*" (employee, large company)
"*When the platform crashes, people immediately say: 'That's why we don't want such systems.'*" (HR expert)
Subcategory: Lack of adequate support and training
Many participants commented on the insufficient preparation and lack of support during the implementation of new systems. This reinforces the feeling of difficulty and leads to negative attitudes.
"*They launched the new system, but no one really trained us. How can we be positive?*" (employee, focus group)
It is directly related to the quantitative results of H4, which show that investments in training increase the success of implementing digital solutions.

Theme 2 emphasizes that the obstacles to digitalization are multifaceted and manifest themselves at the technological, individual and organizational levels. The differences between the groups — HR vs. non-HR employees, small vs. large organizations, culturally prepared vs. unprepared teams stand out significantly. These barriers explain many of the quantitative trends identified in H2, H3, H4, H5, and H6. Qualitative data shows that successful digitalization involves more than just technology, but requires targeted support, training, strategic leadership, and the right organizational culture.

Theme 3: Role of Management and Organizational Culture
The third theme that consistently emerged in the interview and focus group data is related to the leading role of management and organizational culture in digitalization processes. Participants at different levels emphasized that the implementation of digital HR tools is not just a technological project, but a deeply organizational process that depends on leadership, communication, and cultural readiness for change. Several key subcategories emerged in the analysis.

Subcategory: Strategic support from senior management
Participants consistently emphasized that the role of senior management is crucial for the success of digitalization. When management demonstrates different levels of commitment — through resources, clearly set goals, and continuous communication — employees accept the changes more easily and positively.
"*When our director explained why it was important to move to a digital system, people started to take the process much more seriously.*" (HR manager, large organization)
"*If management does not set an example, no one will believe that new tools are a priority.*" (employee, mid-level)
This directly supports the quantitative results of H5, according to which active engagement by senior management is associated with a higher degree of actual implementation.

Subcategory: Importance of communication and explaining goals
Participants strongly stated the need for a clear explanation of why new systems are being introduced, what benefits are expected and what will change in daily work. The lack of effective communication often leads to resistance, uncertainty, increased fears, unlocking stereotypes and spreading concerns.

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"*People are not afraid of the system itself. They are afraid of the ambiguity – what will happen to their work.*" (team leader)
"*When communication is good, resistance also decreases.*" (employee, focus group)
This subcategory is closely related to the quantitative results of H3, related to stereotypes and prejudices.

Subcategory: Role of HR in Change
HR participants often identify themselves as key players who need to mediate between management and employees. They describe themselves as people who "translate" digital solutions and convince employees of their benefits.
"*We are the ones who need to convince both management and people. Without HR, there is no one to drive the process.*" (HR professional)
In some organizations, this role is also taken on by technology teams or team managers who have authority among employees.

Subcategory: Organizational climate that encourages innovation
Another important subcategory is related to the culture of accepting new ideas. In organizations characterized by openness, support and a learning orientation, digitalization is perceived significantly more positively. However, in more conservative, more static or strictly hierarchical structures, the process often encounters barriers.
"*Once we got used to trying new tools, people started to accept them more easily.*" (employee, large company)
"*It's difficult for us — every new thing is met with suspicion.*" (employee, small organization)

Subcategory: Lack of cultural readiness for change
Some participants indicated that organizational culture sometimes works against digitalization — for example, when traditional work habits, suspicion of technology, or reluctance to take risks prevail.
"*We simply don't have a culture of change. Even the best software would be difficult to implement.*" (HR expert)
This confirms the quantitative trends in H3, which link negative stereotypes to low organizational readiness.

Theme 3 clearly shows that digitalization is highly dependent on the quality of leadership and the degree of organizational readiness. Senior management makes the decision for digital transformation, while HR professionals should be mediators in this process, but in reality, the general organizational climate determines whether digital processes will be perceived positively or not. In this sense, the qualitative data provide an explanation for the results of H4, H5, and H6 and provide a complete interpretive framework for the quantitative differences identified.

5. Strategies for digitalization of human resource management

Based on the quantitative and qualitative results, several important strategies can be formulated that support the successful digitalization of human resource management. They relate to both the technological and organizational aspects of the process and provide a basis for sustainable and effective implementation of digital HR solutions.

1. Strategic leadership and active support from senior management
Effective digitalization requires clear leadership, prioritization of the process and consistent support from senior management. This includes: formulating a long-term digital HR vision; providing the necessary resources; communicating the goals and benefits to employees; and management commitment at key stages of the implementation. The results show that organizations with active support from management achieve a significantly higher level of actual implementation and use of HR technologies (confirmation of H5).

2. Investing in training, development and digital competencies
Digitalization can only achieve maximum effect if employees have the necessary skills and the resulting confidence. Effective strategies include: periodic training on new HR platforms; comprehensive programs to de-

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velop basic and advanced digital competencies; creation of internal "digital mentors"; support and adapted training for groups with lower digital confidence. This strategy directly stems from the results of H4.

3. Design and selection of user-oriented digital HR tools
To be adopted and used, HR systems must be intuitive, easy to navigate, adapted to the specific processes in the organization, integrated with other internal platforms. Qualitative data shows that the complexity of the systems and technical difficulties are major barriers.

4. Gradual and phased implementation, supported by robust communication
Effective implementation strategies include pilot projects or small test groups; phased expansion to organizations or teams; regular internal communication about benefits and goals; collecting feedback and adapting processes. This reduces resistance to change and supports cultural readiness (direct link to H3).

5. Creating a cultural environment that supports innovation
The cultural aspect is an important factor shaping the attitude towards digitalization. Effective strategies include: encouraging experimentation and tolerance for mistakes; recognizing and encouraging initiative; introducing mechanisms for the exchange of good practices; creating an organizational climate that rewards adaptability. These elements explain the differences in attitudes between small and large organizations (H6).

6. Optimal use of data for decision-making (data-driven HRM)
Successful HR digitalization leads to a significant improvement in data quality. Effective strategic steps include: developing standards for data collection, processing and analysis; integrating analytical tools into HR processes; using data for strategic planning, forecasting and process improvement. The results of the interviews confirm that improved decision-making is one of the most strongly perceived benefits.

7. Personalizing digital HR solutions according to the organization
Digitalization should not be seen as a universal model. Successful organizations adapt systems to their needs and characteristics; involve end users in the process of developing or selecting a system; avoid overly standardized solutions that do not correspond to real processes.

The proposed strategies are tailored to the specific challenges identified in this study. They unite the technological, human and organizational aspects of digitalization and provide a practical framework for the sustainable development of digital HR processes.

5. Conclusions

The present study shows that the digitalization of human resource management is a comprehensive strategic and cultural process that transforms relationships in the organization. The higher the degree of digitalization of HR processes, the more positive the attitudes towards digital tools, especially in larger and technologically mature organizations. HR specialists demonstrate a higher readiness to adopt digital solutions compared to other employees, and investments in training, development of digital competencies and the active participation of senior management are directly related to the more successful introduction and actual use of HR technologies. At the same time, organizations with low cultural and organizational readiness for change are characterized by more pronounced negative stereotypes, fears and resistance to digitalization, which confirms the central role of organizational culture.

The study contributes to providing further understanding of the digital transformation of organizations related to HRM processes. On a practical level, the results of the study set a clear direction for the development of HRM, which is based on strong strategic leadership, targeted investment in digital skills, the choice of user-oriented HR systems. At the same time, a comprehensive process of transparency and continuous communication, as well as responsible management of risks, especially those related to the increasing use of algorithmic management and the resulting concerns and ethical aspects of AI in HRM. The limitations of the study are related to the fact that the data refer to a single country, as well as the relatively limited sample. However, the

results clearly show that the sustainable digitalization of HRM requires a holistic approach focused on a balance between technology and people and specific organizational goals.

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IMPROVING REVERSE E-LOGISTICS PERFORMANCE IN THE MIDDLE EAST

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Abstract. B2C e-commerce companies are increasing in number due to the significant benefits e-logistics provides, boosting profits and improving customer satisfaction. Moreover, the COVID-19 pandemic increased demand for online shopping due to lockdowns and safety concerns. Despite this, several B2C companies entering the field eventually leave due to inefficient handling of returned products and ineffective reverse e-logistics systems. This article identifies recent methods to improve Reverse Logistics performance for B2C e-commerce firms. The methodology is based on literature review, synthesis, DELPHI, and multi-scoring survey methods. The results showed that management, quality management, organisational structure and culture, IT, customer satisfaction and service, employees, and infrastructure are factors with a direct effect on REL's performance, and this study suggests methods to improve these factors.

Keywords: reverse logistics; e-logistics; e-commerce; reverse e-logistics; reverse e-logistics' performance; supply chain; sustainability

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JEL Classification: D3, I9, L23, Q27

1. Introduction

The e-logistics sector has demonstrated a significant impact on the global economy in recent years. Its importance for e-commerce and logistics operations. Approximately 10 per cent of global GDP is accounted for by the global e-logistics market (Wu et al., 2017). The projections for future growth in the e-logistics sector are promising. Experts in sustainable logistics and e-commerce indicate that the ongoing digital transformation will not only elevate logistics efficiency but also enhance overall economic productivity (Mutambik, 2025). Efficient reverse e-logistics (REL) systems are essential for implementing e-logistics effectively. A company's REL can help increase profits, improve the sustainability of its resources, and enhance customer satisfaction by improving operational performance. In other words, if a company can maintain an efficient REL system, its e-logistics system will be improved, making it a better B2C e-commerce company. To date, there is a shortage of literature in the field of REL, especially in developing countries such as the Middle East. The purpose of this article is consequently to detect means to enhance the performance of REL systems for B2C e-commerce companies. This results in the research question (RQ): how can REL's systems be improved for B2C e-commerce enterprises operating in the Middle East? The methodologies used are literature review, synthesis, DELPHI, and multi-scoring survey methods.

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2. Review of Literature

2.1 Aspects of Reverse E-Logistics

Reverse logistics (RL) is a vital component of the supply chain management framework, addressing the complexities of product returns from customers to manufacturers. This process encompasses not only the physical return of goods but also various managerial and logistical considerations essential for optimising efficiency and maximising value recovery. Basically, reverse logistics (RL) involves moving finished products through the supply chain from customers to manufacturers (Panghal et al., 2022). Recent studies emphasise the significance of reverse logistics as a system that manages both forward flows from suppliers to customers and reverse flows associated with returned products from customers back to suppliers. In a more typical sense, RL refers to the tasks performed by the organisation to reduce waste, recycle, replace, reutilise, and eliminate hazardous materials (Zvarikova et al., 2024; Herrada-Lores et al., 2025). A broader perspective of RL encompasses all logistics operations that involve waste management or waste removal (Melo et al., 2022). The RL systems provide logistical value and an infrastructure capable of identifying, running, and selecting waste through all the supplementary value phases of the reverse channels, in addition to resupplying the forward supply chains (Melo et al., 2022).

Additionally, the management of reverse logistics is increasingly recognised as crucial for customer satisfaction and retention. A study by Mahindroo, Samalia & Verma (2018) indicates that understanding return frequencies and the resources committed to reverse logistics can significantly influence overall strategic performance in supply chains (Mahindroo, Samalia & Verma, 2018). RL manages the influx, storage, and removal of goods that are not considered a priority, along with associated data, utilising the conventional supply chain to restore value or dispose of them properly. RL can be employed to address the issue of unnecessary and non-renewable resources (Wardani et al., 2022). When a product cannot be used to generate revenue or cannot be reused or recycled in a new production cycle, reverse logistics is involved in its recovery (Lingaitienė, Burinskienė & Davidavičienė, 2022). In recent years, there has been growing interest in reverse logistics from both theoretical and practical perspectives, driven by ecological benefits. Reverse logistics is a process that reduces the environmental harm associated with the recovery of materials. Reverse logistics also offer ecological benefits by increasing product recycling and recovery, thereby reducing resource use. In reverse logistics, responsibilities or objective systems that encompass environmental, economic, and social features have emerged over time from a reverse flow of goods only. Firstly, reverse logistics aims to minimise waste by reutilising and recycling as much as possible. Subsequently, it seeks to provide customers with value-added service by meeting their requirements, whether it is for product returns or recycling (Lai et al., 2022). The efficient use of resources is associated with enhanced economic performance (Ivanova, Rogaczewski & Lutsenko, 2022). The COVID-19 pandemic has driven an increase in online buying, thereby boosting reverse logistics. Such unexpected crises generate new challenges and require finding other ways to operate (Zamfirache et al. 2025; Herrada-Lores et al. 2025).

A reverse e-logistics (REL) approach is based on reverse logistics. It is often referred to as reverse logistics with ICT activation. According to REL, products flow from consumption to production in reverse order after an online order is placed (Morgan et al., 2018). The REL is an element of logistics that focuses on reducing resource use by recycling, discarding waste, re-establishing, and refabricating products sold through e-commerce (Mahindroo, Samalia, & Verma, 2018). As part of its role, REL is responsible for ensuring that e-commerce firms' supply chain procedures are effective and efficient. In other words, focusing on the reverse flow of materials aligns with REL's goal of maximising supply chain value by increasing reverse flow (Han & Trimi, 2018). REL is responsible for the recovery of consumer goods that have reached the end of their lifespans (Batarfi, Jaber & Aljazzar, 2017). By reducing costs, improving customer satisfaction, and improving internal processes, an effective REL's management can improve organisational performance (Han & Trimi, 2018). It is asserted that the REL can contribute to the recovery of economic value in an operational and strategic manner, providing services with enhanced value to reduce risks and enhance business reputation (Da Silveira Guimarães & Salomon, 2015). By integrating economic, environmental, and legal services, REL streamlines the return of products back into the business cycle. REL is the most popular and modern form of reverse logistics.

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2.2 Barriers to Improving REL's Systems

It is the management's responsibility to make sure REL's systems operate effectively within the organisation. Despite this, management faces major obstacles, including a lack of commitment, inadequate strategic planning, limited experience, and a reluctance to accept change (Sirisawat & Kiatcharoenpol, 2018). A manager's influence, governance, and emergency response can affect REL's operations. It is viewed as a substantial barrier to an effective settlement of REL when managers from several departments lack interest, information, awareness, and engagement (Waqas et al., 2018).

The presence of unskilled employees appears to be the cause of negative REL performance in some companies (Sirisawat & Kiatcharoenpol, 2016). It is considered valuable for a company to have skilled employees capable of handling REL's supply chain operations by involving them in decision-making, providing appropriate training, improving communication and coordination, and enhancing their competencies (Waqas et al., 2018). It is crucial to continuously monitor the supply chain encompassing REL's systems and the company's activities to maintain the maximum number of workers, as any reduction will negatively impact REL's performance (Bal & Satoglu, 2018). Incompetence or lack of training can lead to poor employee performance. In turn, this will negatively impact REL's performance because of unprofessional, unskilled, and inexperienced employees.

The fact that IT processes are lacking, outdated technology is used, and poor infrastructure are the main factors affecting REL's effective settlement. To solve this problem, companies should invest more in research and development. A firm's technological systems must also be updated constantly. In fact, REL's performance is strongly influenced by the information technology system (Batarfi, Jaber & Aljazzar, 2017). IT is required to facilitate electronic commerce, and thus, REL cannot operate without strong IT systems. REL's performance is adversely affected by several factors related to customer returns, including warranty issues (Pandian & Abdul-Kader, 2017). Returned goods and warranty repair costs can negatively impact REL's operations. A poor guarantee, on the other hand, will undermine customer confidence in the product, making them less likely to purchase it. Because a significant portion of returns is due to warranty claims, many firms began combining REL tactics with their own strategies and supply networks. Companies handle REL differently, especially regarding product warranties, because it affects their sales constantly (Panigrahi et al., 2018). The return policy must include other objectives, such as recycling and disassembly, rather than being limited to defective goods (Waqas et al., 2018). Since providing a guarantee to online customers is seen as a "reassuring factor" for subsequent transactions, its significance is beyond debate. However, to avoid unnecessary returns and related costs, such warranties should be carefully drafted.

The effective settlement of REL activities is recognised as hindered by defection, the removal of amenities, infrastructure, and typical employed resource markets (Chinda, 2017). The supply chain and a company's infrastructure are integrally linked. Businesses with infrastructure issues struggle to manage recalled or returned goods, which negatively affects REL's performance (Sirisawat & Kiatcharoenpol, 2016). Therefore, a company should be able to manage returned goods effectively, provided it has a robust infrastructure. Nevertheless, the lack of infrastructure will affect the organisation's capacity to handle these returns, resulting in high costs and losses (Prakash & Barua, 2015). For reverse e-logistics to be successful, infrastructure is required. Without strong infrastructures, businesses won't be able to handle REL procedures effectively, which would seriously jeopardise REL's performance. When implemented properly, organisational structure has a good impact on REL's performance. However, if the company has a poor structure, that will be seen as a roadblock to REL's effective performance (Morgan et al., 2018). The norms, policies, procedures, and culture of collaboration between managers and employees within an organisation affect how well REL performs (Waqas et al., 2018). The effectiveness of REL is directly associated with a strong institutional framework that recognises the fundamental requirements of its employees, activities, and skills (Cannella, Bruccoleri, & Framinan, 2016). A properly designed, understandable, and effective institutional framework will give businesses a competitive edge and make a significant difference in earnings (Prakash & Barua, 2015). Companies should understand that there is no ideal organisational structure. The goals, offerings, and efficiency of each company's supply chain all influence its organisational structure. However, the development and implementation of a successful organisational structure are facilitated by a positive corporate culture.

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Quality products should not be exchanged for quantity, as effective quality supervision and control methods can achieve this (Prakash & Barua, 2015). If a company's quality management is weak or nonexistent, the volume of returned goods may affect the availability of these products and, thus, the effectiveness of REL (Waqas et al., 2018). Enhancing product quality through efficient quality control and evaluation systems increases client retention, which in turn increases client satisfaction (Vlachos, 2016). By maintaining product quality through effective management systems that track customer feedback and needs, businesses can add value to their customers (Mahindroo, Samalia & Verma, 2018).

3. Methodology

The purpose of this article was to detect means to enhance the performance of REL systems for B2C e-commerce enterprises. The created research question (RQ) was: how can REL's systems be improved for B2C e-commerce enterprises operating in the Middle East? As such, to explore the study's goals and address its research question, the preceding section of this article presented theoretical background. To identify means to enhance REL's performance, the views of seven professionals in the field of REL were considered using two methods: the Delphi method and the multi-criteria scoring method. The chosen criteria were: a minimum of a master's degree in supply chain or logistics management; at least 10 years of professional experience in logistics or supply chain management; at least 5 years of experience in reverse e-logistics; and holding a top management position within the organisation.

There are two primary rounds in the DELPHI process. Round 1 involves gathering responses from supply chain specialists. Following the determination of the experts' consensus and round 1 result, a second questionnaire is delivered in round 2 to further analyse the selected parameters. In round 1, experts were questioned about the top 15 elements that affect or can enhance the performance of reverse e-logistics. The same experts were then invited to complete a questionnaire with two primary elements in round 2. Part A asks for their view on how important the aforementioned elements are to REL's performance, and Part B assesses the weight of various REL operations on business performance. In round 1 of the DELPHI technique, experts were required to rank the elements they believed had the most influence on REL's performance before responding to the round 2 questionnaire.

The same professionals were then asked to score the factors and their associated criteria using a multiple-criteria approach. The multi-criteria scoring technique was utilised to analyse the specifics of how the identified aspects affecting REL's performance could be enhanced. A scale of 0 to 10 was used, with 0 indicating a low likelihood of an effect and 10 indicating a high probability. The total points attributed to the eight assigned factors must add up to 10. The same holds for criteria scoring, where each component must have a total score of 10 points. Data validation ensures the sum is no greater than 10.

4. Results & Discussions

The experts provided a total of 24 different variables in round 1 of DELPHI. The elements that have been proposed as possibly affecting REL's success in the first round of DELPHI are summarised in Figure 1 below.

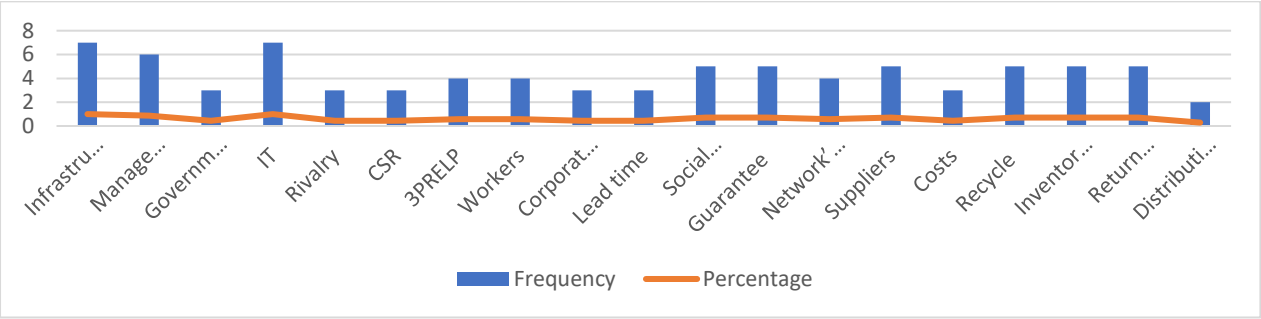


Figure 1. Suggested factors impacting REL's performance in the first round of the Delphi
Source: created by the authors

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The percentage details by factor: Infrastructure 100%, Management 85.71%; Government policies 42.85%; IT 100%; Rivalry 42.85%; CSR 42.85%; 3PRELP 57.14%; Workers 7.14%;; Corporate image 42.85%; Lead time 42.85%; Social network 71.42%; Guarantee 71.42%; Network's capability 57.14%; Suppliers 71.42%; Costs 42.85%; Recycle 71.42%; Inventory management 71.42%; Return policy 71.42%; Distribution channels 28.57%; Transportation costs 42.85%; Internet Connection 71.42%; Client satisfaction 100%; Quality management 57.14%; Organisation structure/environment 57.14%. Elements with less than 51% consensus were disregarded, while relevant ones were grouped into the same category. One factor, for instance, was the guarantee and return policy. The factors were analysed and categorised, and they were then condensed into 10 major ones, which are: Management, IT, infrastructure, external intermediary reverse e-logistics, organisational hierarchy and environment, quality management, inventory management, workers, return policies and guarantees, and customer retention. Low agreement is indicated by answers below 4, medium agreement is indicated by answers between 5 and 6, and high agreement is indicated by answers between 7 and 9, with answers over 7 indicating high agreement. When the value is between 51% and 100%, consensus is attained.

The consensus was calculated using the interquartile range (IQR). The IQR calculates a data series' middle 50 values. The IQR is a measurement of exemptions or the range of values that most commonly occur. IQR is determined by subtracting the first quartile from the third quartile, according to the following formula: IQR = Q3 – Q1. When the IQR value is less than or equal to one (IQR 1), it is assumed that there is agreement among the experts' opinions and that the factor in question will have an effect on REL's performance. The relative judgment on the variables affecting REL's performance is summarised in Table 1 along with the IQR measurement.

Table 1. IQR measurement of factors influencing REL's performance

Factor	Mean	IQR	Decision
Management	6.6	1	Not rejected
Workers	6.5	1	Not rejected
IT	7.0	0	Not rejected
3PRELP	4.5	5	Rejected
Inventory Management	4.6	6	Rejected
Return Policy/Guarantee	5.9	5	Rejected
Infrastructure	8.5	1	Not rejected
Institutional structure/culture	7.2	1	Not rejected
Client satisfaction	8.72	1	Not rejected
Quality management	6.5	1	Not rejected

Source: created by authors

The management, personnel, infrastructure, organisational hierarchy/environment, client satisfaction, quality management, and IT all have an IQR of 1, which states they are all acknowledged and taken into consideration for further investigation, as can be seen from the table above. Inventory management had an IQR of 6, external reverse e-logistics and return policy/guarantee had an IQR of 5, both of which indicate that they are disregarded because of an absence of consensus. The mean is computed once the last set of factors has been determined. Table 2 below displays the acknowledged criteria and their relative means.

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Table 2. Accepted factors influencing REL's performance and their relative means

Factor	Mean
Client satisfaction	8.72
Infrastructure	8.5
Org. structure/environment	7.2
IT	7.0
Management	6.6
Workers	6.5
Quality management	6.5
Return Policy/Guarantee	5.9
Inventory Management	4.6
3PRELP	4.5

Source: created by the authors

Accordingly, factors that affect reverse e-logistics performance can be ranked according to consensus acceptance and mean calculations as follows: customer satisfaction (mean=8.72) is the most crucial factor to take into account, followed by infrastructure (mean=8.5), organisational structure/culture (mean=7.2), IT (mean=7.0), and management (mean=6.6), whereas workers and quality management are equally important (mean=6.5).

In order to discover and locate the precise solutions in the framework of the research, it was then decided to conduct another multi-criteria scoring questionnaire. How might the factors discovered improve REL's performance? Experts were questioned. Therefore, a third questionnaire was issued to the professionals, asking them to elaborate on how the seven factors were being improved. The eighth component (Return Policy), which was thought to have a major impact on REL's performance in addition to the seven previously mentioned criteria, was also added. First, the experts were asked to rank the significance of each of the 8 factors on REL's performance on a scale of 0 to 10. Experts were given 10 points to score on the proviso that they were spread evenly among the identified factors, meaning that no factor may receive more than 10 total points. Table 4 summarises their results.

Table 4. Experts' scores of factors that affect REL's performance

Factor	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Mean Average
Client Satisfaction	3	2	2	2	3	2	2	2.285714
Workers	0	1	1	1	0	2	0	0.714286
Infrastructure	2	2	2	2	3	2	1	2.00
IT	2	2	1	1	2	2	2	1.714286
Management	1	1	1	2	0	0	1	0.857143
Org. Structure & Culture	2	2	1	2	2	2	2	1.857143
Quality Management	0	0	1	0	0	0	1	0.285714
Return Policy	0	0	1	0	0	0	1	0.285714
Total Points	10	10	10	10	10	10	10	10

Source: created by authors

The experts claim that, in order of importance, the following factors have an effect on REL's performance: client satisfaction (Mean= 2.28), infrastructure (Mean= 2.00), organisational structure and culture (Mean= 1.85), IT (Mean= 1.71), management (Mean= 0.85), employees (Mean= 0.71), quality management (Mean= 0.28), and return policy (Mean= 0.28). Then, experts were required to rate the criteria of factors in order to analyse methods of enhancing the factors. Figure 2 below provides a summary of the conceptual research model that has been chosen.

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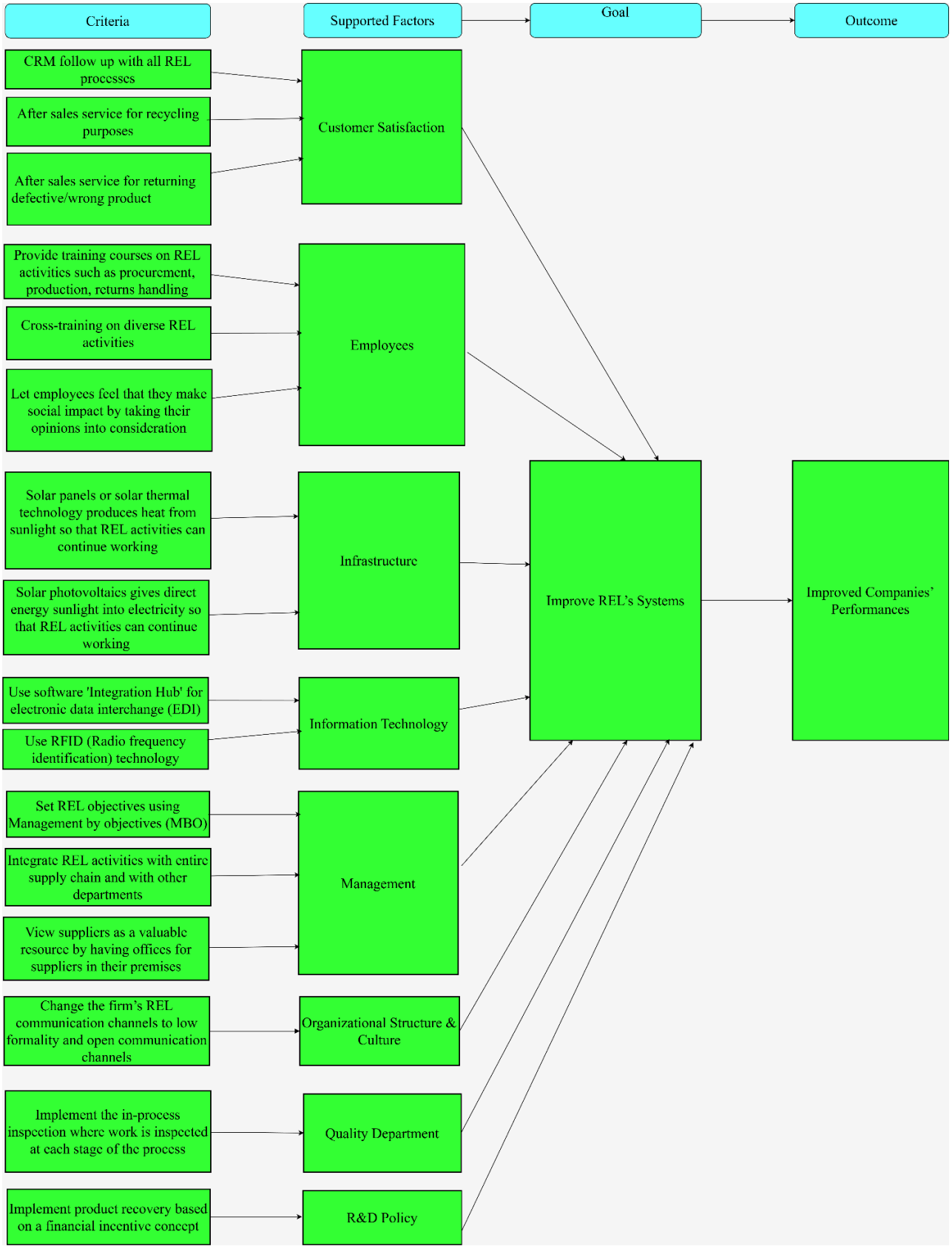


Figure 2. The conceptual research model

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The customer satisfaction factor must be improved before managers can increase the performance of REL's systems. This can be done by doing the following: By monitoring all REL operations, managers must concentrate on the integration of the CRM with REL's systems (returns, recalls, repairs, re-packaging for restock or resale, recycling and disposal, etc.). Following that, management must combine REL's systems with its after-sales service, especially for recycling motives. Finally, managers are responsible for assigning after-sales service for returning defective or incorrect products obtained from REL's operations.

The following actions can be taken to improve employee performance, which is the second thing managers must focus on the following.
First, managers must offer all workers in their supply chain, especially those working with REL's processes, training sessions on REL operations like procurement, production, and returns processing. To help employees get more familiar with REL's systems, directors must concentrate on providing cross-training on a variety of REL activities.
Second, managers must provide employees a sense of social effect by taking their feedback into account while building REL's systems.
Third, managers need to focus on enhancing their infrastructure, which may be done by implementing solar panels or solar thermal technology, which generates heat from sunlight so that REL's operations can go on uninterrupted. To ensure uninterrupted REL operations, managers must think about putting up solar photovoltaic systems that convert sunshine directly into electricity.
Fourth, managers need to work to enhance their Information Technology (IT), which can be done by making it easier to keep in contact with all of their key stakeholders, including KPI providers. Managers must adopt the software "Integration Hub" for electronic data interchange (EDI). Managers should consider implementing RFID (Radio frequency identification) technology, which uses radio waves to read digital data encoded in RFID tags or smart labels. This technology automatically identifies objects, gathers data about them, and inputs that data into computer systems with little to no human involvement.
Fifth, managers need to work on horning their management abilities by connecting REL's activities with those of the entire supply chain and other departments. Managers must have strong leadership and interpersonal skills. Managers can treat suppliers as valued resources by creating supplier offices on their premises.
Sixth, managers need to focus on enhancing the organisational structure and culture. Managers need to consider converting the organisation into an organic one, where the REL communication channels are transformed into low-formality, open channels.

Managers can implement in-process inspection, which involves inspecting work at each process stage and immediately stopping production if even one defective product is found. This action will decrease the number of incidents involving damaged products. To improve the return policy, managers must establish a product recovery that relies on financial motives. This signifies that the business should provide the consumer a discount on a new purchase or just a set amount of money as a reward whenever they return a product for recycling.

Conclusions

Numerous problems must be resolved before B2C e-commerce can be profitable. Reverse e-logistics (REL) is arguably the most challenging aspect of B2C e-commerce. REL has a number of advantages despite the difficulties that it presents. For instance, REL leads to higher earnings, a stronger position in the e-commerce sector, an uptick in consumer satisfaction, a drop in resource utilisation, and improved resource sustainability for businesses. Therefore, identifying ways to improve REL's performance is necessary and was the objective of this study. Two more analyses, the multi-criteria evaluation DELPHI and multi-criteria scoring, were conducted to learn more about how such factors might be improved. The conclusions regarding the variables affecting REL's performance were verified through the DELPHI method. According to experts, there are seven factors that have a significant effect on REL's systems: management, quality management, institutional structure and culture, IT, client satisfaction and service, personnel, infrastructure, and staff. After that, a detailed analysis of how the discovered elements that are positively connected with REL's performance could be improved was conducted using the multi-criteria scoring approach. From a management perspective, B2C e-commerce businesses operating in advanced nations, such as those in the Middle East, which still experience some political conflicts and economic instability, can apply the model and conclusions of this dissertation. A limitation of this

study was that Middle Eastern countries still lack scientific research and results. Therefore, the recommended future research is in Middle Eastern countries, more specifically, in the field of B2C e-commerce and REL's activities.

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