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Table of Contents

Rebuilding Security after War: Economic Reconstruction and Structural Transformation in the Karabakh Region	6
<i>Nargiz Hajiyeve, Mahmud Nuriyev</i>	
Megatrends, circular economy business models, and sustainability regulation in business.....	21
<i>Suvi Sivén, Jukka Sirkiä</i>	
Generative AI in Higher Education: Adoption and Impact of Custom GPT Chatbots on Student Learning in Management Accounting and Finance	32
<i>Isabel Lausberg, Alexander Bönner, Timur Gümüş</i>	
Learning Attitudes and Voluntary Engagement among Mothers Recently Returning to the Labour Market.....	49
<i>Ágnes Csenge Fehér, Ágnes Wimmer, Zoltán Buzády</i>	
Comparative analysis of the financial performance and profitability of Hungarian and Polish agricultural enterprises	63
<i>György József Mudri, Aranka Baranyi</i>	
Has COVID-19 Transformed Crisis into Digital Acceleration? A Decade-Long Analysis of ERP Adoption across Countries.....	81
<i>Aleksandra Radić, Sanela Arsić, Đorđe Nikolić, Lidija Krstić</i>	
Digital Transformation Strategies for Azerbaijani SMEs to Strengthen Integration into Global Value Chains	92
<i>Aynur Garayeva, Elvin Garayev</i>	
To examine the influence of CSR responsibility on consumer behavioral intention	104
<i>Harrison Manga</i>	
Integrating artificial intelligence into agriculture in the EU	120
<i>Zsuzsanna Deák, Ferencz Árpád, Attila Gábor Ferencz</i>	
Gender Equality and the Knowledge Economy: A Structural Framework for Sustainable Social Futures	133
<i>Fidan Safarova</i>	
Empirical aspect of predictive maintenance applied to complex manufacturing systems	149
<i>Ciortea Elisabeta Mihaela</i>	

The Power of Color: Psychological and Marketing Effects of Color in Consumer Decision-Making.....	163
<i>Anna Maria Ugron</i>	
Life-Cycle Cost Analysis And Health Technology Management Of Diagnostic Medical Equipment In Ugandan Public Hospitals: Financial Sustainability Challenges And Strategic Opportunities For Improvement.	177
<i>Winniefred Akello, Yue Wu</i>	
Design and Implementation of a Personalized Data Visualization System for Higher Education	195
<i>Olta Llaha, Esmeralda Kadena, Eleni Papapano</i>	
The role of small and medium-sized enterprises (SMEs) in the manufacturing sector, their competitiveness, and challenges in Ghana.....	206
<i>Bazark Abdallah, Wu Yue</i>	
An Empirical Analysis of Consumer Preferences For Salty Snacks	225
<i>Csaba Hamza</i>	
Online Platform Data for Tourism Research in Northern Albania: A Comparative Analysis of Booking.com and TripAdvisor.....	243
<i>Fatjona Kroni, Ermira Kalaj, Erjola Barbullushi</i>	
Competitive sustainability or sustainable competitiveness: the nontrivial triviality we are all searching for.....	254
<i>Csilla Mile, Zoltán Bodrog</i>	
Addressing the Skills Gap in Tourism: A Comparative Analysis of Vocational Education in Albania	268
<i>Alkida Hasaj, Sead Baraku</i>	
Artificial Intelligence and the Reconfiguration of the Accounting Profession in the Western Balkans: An Extended Model of Task Automation, Decision Augmentation, Skill Renewal, and Employment Resilience.....	282
<i>Elidiana Bashi, Sead Baraku</i>	
From Sustainability Metrics to Decision Intelligence: A Framework to Integrate Green IT into Enterprise Infrastructure Planning	295
<i>Shreya Anchlia</i>	
Socioeconomic profile and development dynamics of beekeeping families in Northern Albania	312
<i>Sidita Zaganjori, Ariana Striniqi</i>	

From Motorsport to Entertainment Brand - How Drive to Survive Contributed to Formula 1's Growing Popularity	323
<i>Lili Belkovics, István Takács, Krisztina András</i>	
Turning Crisis into Opportunity: Tourism-Led Nation Branding in Türkiye	333
<i>Irina-Maria Cosma</i>	
From War to Cooperation: Crisis-Driven Innovation and Romania's Modernization Model	339
<i>Nicoleta Chicinaş</i>	

Rebuilding Security after War: Economic Reconstruction and Structural Transformation in the Karabakh Region

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Abstract: This paper examines the reconstruction of the Karabakh region through the lens of economic law, focusing on the relationship between legal frameworks and post-conflict economic recovery. It argues that reconstruction in Karabakh is not limited to infrastructure development but involves the re-establishment of a functional legal-economic order. Drawing on institutional and post-conflict reconstruction literature, the study highlights the role of property rights, investment regulation, and governance mechanisms in reducing uncertainty and enabling sustainable economic activity. The analysis further explores state-led investment strategies, industrial zones, and incentive regimes as transitional tools that require legal consolidation to ensure long-term effectiveness. By situating Karabakh within broader theoretical debates, the paper demonstrates that economic security in post-conflict settings depends on the credibility of legal institutions. The findings suggest that the sustainability of reconstruction efforts will ultimately depend on the transition from incentive-driven growth to institution-based economic stability.

Keywords: Karabakh reconstruction; economic law; post-conflict recovery; property rights; investment incentives; institutional development

1 Introduction

The reconstruction of the Karabakh region following the 2020 war represents not only a process of rebuilding physical infrastructure, but a deeper challenge of restoring economic order under conditions of institutional disruption. Post-conflict reconstruction, as widely recognized in the literature, is inherently multidimensional, involving the simultaneous re-establishment of governance, economic systems, and legal frameworks necessary for long-term stability [1]. Yet, despite a substantial body of research on post-war recovery, the relationship between economic reconstruction and legal order remains insufficiently theorized in specific regional contexts such as the South Caucasus.

Existing scholarship has consistently emphasized that post-conflict economic recovery differs fundamentally from standard development processes. As Del Castillo argues, reconstruction is an intermediate and fragile phase in which policies must be carefully sequenced to avoid a relapse into instability, rather than simply promoting growth [2]. Similarly, Coyne highlights that successful reconstruction depends on the establishment of institutional prerequisites, particularly property rights, rule of law, and market-supporting institutions, without which economic systems fail to become self-sustaining [3]. These insights align with the broader institutionalist tradition associated with Acemoglu and Robinson, where the quality of institutions rather than the availability of resources determines long-term economic outcomes [4].

However, much of this literature has focused either on macro-level reconstruction strategies or on international interventions, often overlooking the legal-economic mechanisms through which reconstruction is operationalized. In particular, the role of economic law property regimes, investment regulation, and governance structures has been underexplored as an independent analytical category, especially in post-Soviet and occupation-affected territories. As some studies note, even in areas such as decentralization and local governance, there remains a significant gap in understanding how legal institutions function in post-conflict settings beyond isolated case studies [5].

The case of Karabakh highlights precisely this gap. During the period of occupation, the region was characterized by the absence of legitimate legal authority and the emergence of informal and extractive economic practices. As documented in Hajiyeva's work, economic activities during this period involved systematic exploitation of resources, unregulated property use, and the erosion of formal legal-economic structures [6]. These dynamics did not merely distort economic outcomes but fundamentally altered the institutional landscape upon which post-war reconstruction must now be built.

The Azerbaijani government's "Great Return" strategy and large-scale public investment programs represent an effort to reverse these dynamics by combining infrastructure development with economic revitalization. Significant financial

resources have been directed toward transport corridors, energy systems, industrial zones, and the resettlement of internally displaced persons. In principle, such policies aim to transform Karabakh into a sustainable economic hub. Yet, as the broader literature on post-conflict reconstruction suggests, investment alone is insufficient. Large-scale infrastructure projects, while necessary, do not automatically generate sustainable development if they are not embedded within a stable legal framework. Reconstruction experiences in other contexts demonstrate that focusing primarily on physical rebuilding without institutional consolidation leads to partial or fragile recovery [7].

The core problem, therefore, lies in the fragile and often underdeveloped link between economic reconstruction and legal order. Legal uncertainty particularly regarding property rights, contract enforcement, and regulatory governance introduces risks that undermine both domestic and foreign investment. From an economic law perspective, this uncertainty increases transaction costs and limits the emergence of formal market structures. The transition from a conflict-affected territory to a functioning economic space requires not only capital investment but the creation of a predictable legal environment in which economic actors can operate with confidence.

This paper addresses this gap by examining the reconstruction of Karabakh through the lens of economic law. Its central research aim is to analyze how legal frameworks specifically property rights regimes, investment law, and governance mechanisms shape the trajectory of post-conflict economic recovery. In doing so, it contributes to the broader literature by situating legal institutions not as secondary instruments of policy implementation, but as foundational determinants of economic transformation.

2 Literature review and theoretical framework

Post-conflict recovery is usually discussed in terms of finance, infrastructure, and public administration. That vocabulary is incomplete. Economic recovery after war is not simply a question of rebuilding roads, reopening markets, or restoring production; it is equally a question of restoring the legal architecture within which economic life becomes possible. Del Castillo's work remains important here because it insists that post-conflict reconstruction is not a standard development phase, but an intermediate and fragile period in which policy must be directed first toward preventing relapse into disorder rather than maximizing growth in the ordinary sense [8]. This point matters for Karabakh. The issue is not only how quickly reconstruction proceeds, but whether the institutions governing land, contracts, investment, and public authority are strong enough to convert public spending into durable economic activity.

The relevance of economic law in this setting follows from a simple fact: in post-war territories, the central economic problem is uncertainty. War destroys assets, but it also destroys records, administrative continuity, and confidence in enforceable rules. Where ownership is disputed, where registries are incomplete, where contracts are difficult to enforce, and where the reach of the state has only recently been restored, investment becomes cautious, selective, and often short-term. Fitzpatrick and Fishman put the matter sharply in their work on land policy after armed conflict: conflict alters land distribution and governance systems, complicates title through displacement and secondary occupation, and allows political actors to consolidate control in the absence of effective legal oversight [8]. In such a setting, economic law is not an abstract superstructure placed above recovery; it is one of the conditions of recovery itself.

This is why the literature that links institutions to post-conflict stability remains directly relevant. Lake's analysis of post-conflict institutions in eastern Congo turns on a broader proposition: institutions matter because they reduce uncertainty in environments where commitments are otherwise weak and violence remains a latent possibility [9]. The same logic applies to economic life. A functioning market is, in part, a system of credible commitments. People invest, exchange, lend, lease, insure, and rebuild when they believe that rules will outlast the transaction. Once that belief erodes, economic actors shift toward informality, political protection, or exit. For post-conflict recovery, then, the restoration of law is not merely a matter of justice; it is also a means of lowering transaction costs and extending the time horizon of economic decision-making.

2.1 Economic Law and Institutional Recovery

At this point the literature becomes more complicated, and more useful. The rule of law is often treated in peacebuilding discourse as an uncomplicated good, but the more recent scholarship is less naïve. In the *European Journal of International Security*, for example, it has been argued that rule-of-law reforms in post-conflict settings may reproduce existing inequalities when formal legal institutions are introduced into deeply unequal social orders without adequate attention to access, enforcement, and distributive consequences [10]. This criticism should be taken seriously in the Karabakh case. Legal reform is indispensable, but law that exists only on paper, or law that secures the position of the most resourceful actors first, can harden rather than resolve post-war asymmetries. A serious economic-law approach therefore requires more than legislation; it requires enforceability, administrative capacity, and equal access to remedies.

The most concrete legal issue in post-conflict recovery is usually property. Housing, land, and property claims sit at the point where return, investment, reconstruction, and legitimacy intersect. Recent work in *World Development* shows that post-conflict restitution frameworks are often poorly aligned with actual tenure conditions, especially where records are incomplete, displacement has been

prolonged, and the pre-war land order has already been transformed by conflict [11] That insight is especially relevant to Karabakh. After decades of occupation, the region does not present a normal legal environment in which pre-existing entitlements can simply be reactivated. The difficulty lies not only in identifying title, but in reconnecting legal title to lived social realities: destroyed settlements, absent populations, degraded land, altered use patterns, and the institutional consequences of prolonged separation from the Azerbaijani legal order.

The Karabakh case gives this literature a sharp practical edge. During the years of occupation, the region was marked by the absence of Azerbaijan's lawful institutional framework and by forms of resource use and property control that did not operate within the legal and regulatory system of the Azerbaijani state. Hajiyeva's study of economic activities during the occupation is significant precisely because it documents this dimension of the problem: the issue was not only economic loss, but the long-term distortion of legal-economic relations through unauthorized exploitation, unregulated use of property, and the erosion of formal governance structures [12] That legacy matters now because post-conflict reconstruction begins not from an intact legal baseline, but from a field already shaped by institutional discontinuity.

The present reconstruction drive in Karabakh has been organized through a strong state-led framework. The First State Program on the Great Return defines the revival of the liberated territories as part of Azerbaijan's national development priorities and links resettlement, infrastructure, and economic activity in a single programmatic structure.⁷ Official figures further indicate that, from 2021 through the end of 2024, more than 19 billion manats had been allocated for the restoration of Karabakh and East Zangezur [13] These measures show that the Azerbaijani state understands the scale of the reconstruction task. Yet the legal dimension remains decisive. Public expenditure can build roads, utilities, industrial sites, and housing stock; it cannot by itself settle ownership claims, guarantee future transactions, create credible investment expectations, or resolve disputes over use and entitlement. Those are legal and institutional tasks.

This is also where the existing Karabakh-specific scholarship, though still limited, is instructive. Guliyev's recent study of post-conflict resettlement in Karabakh describes the reconstruction challenge in terms that go well beyond physical damage, emphasizing mine contamination, destroyed civilian infrastructure, and the difficulty of rebuilding livelihoods under hazardous and institutionally demanding conditions. [14] Hovhannisyan and Musavi, in their discussion of property restitution after the Second Karabakh War, make a related point from another angle: technical restitution mechanisms alone are not enough. Property restitution in post-conflict settings must engage not only with titles, registries, and cadastral records, but also with legislation, enforcement, social perceptions of justice, and the material realities of return [15]. This line of argument is close to the core of the present paper. The Karabakh case cannot be understood adequately if reconstruction is reduced to

engineering and budgetary planning. It is, at the same time, a problem of legal ordering.

For that reason, the importance of economic law in Karabakh is not limited to investment promotion in a narrow sense. It has at least four wider functions. First, it stabilizes expectations by clarifying property relations and enforceable rights. Second, it disciplines reconstruction by placing public and private economic activity within a framework of predictable rules. Third, it mediates return by connecting resettlement to legally recognized claims in land, housing, and local economic life. Fourth, it limits the risk that post-war development will become administratively impressive but institutionally shallow. Where these legal foundations remain weak, reconstruction may proceed in visible form while remaining fragile in substance.

The broader scholarly literature has already supplied many of the conceptual tools for this analysis, even if it has not yet applied them fully to Karabakh. Del Castillo explains why post-conflict economic policy cannot be treated as ordinary development policy [15] Fitzpatrick and Fishman show why land and property governance are central rather than peripheral to recovery.² Joireman and Tchatchoua-Djomo demonstrate that restitution frameworks often misfire when they fail to account for the altered realities of post-conflict tenure systems [16]. Lake shows why institutions matter where uncertainty and the risk of renewed violence remain high [17].

That is why the study of economic law in post-conflict Karabakh is not a secondary refinement of a reconstruction story already understood in material terms. It goes to the heart of the matter. The practical question is not whether the region will be rebuilt physically; rebuilding is already underway. The more difficult question is whether that reconstruction will be translated into a stable legal-economic order capable of sustaining return, encouraging investment, and embedding economic activity within institutions that can endure beyond the first wave of state-led recovery.

2.3 Research Gap

Although extensive research exists on post-conflict reconstruction, most studies focus on governance reform, economic recovery, or peacebuilding interventions. Limited attention has been devoted to economic law as an independent determinant of reconstruction outcomes. Furthermore, Karabakh remains largely absent from comparative studies of post-conflict institutional recovery. This study addresses this gap by examining how legal institutions influence economic security, investment behavior, and reconstruction outcomes in the Karabakh region.

3 Methodology

This study employs a qualitative case study approach to examine the role of economic law in post-conflict reconstruction in the Karabakh region. Karabakh was selected as a critical case because reconstruction, institutional restoration, and economic reintegration are occurring simultaneously following the 2020 war. The analysis is based on document analysis of academic literature, Azerbaijani legislation, state programs, official reports, and policy documents related to reconstruction and economic development in Karabakh. Key sources include the Great Return Program, Ministry of Economy reports, industrial park documentation, and studies on post-conflict recovery and institutional development. The study examines reconstruction through three analytical dimensions: (1) property rights and legal certainty, (2) investment incentives and regulatory frameworks, and (3) governance mechanisms supporting economic recovery. These dimensions were selected based on the institutional economics and post-conflict reconstruction literature, which identifies legal institutions as essential for reducing uncertainty and facilitating sustainable development. The study relies primarily on secondary data and official documents. While this limits the ability to evaluate long-term outcomes and stakeholder perceptions, it allows for a systematic assessment of the legal and institutional foundations underpinning the reconstruction process in Karabakh.

4 Findings and Discussion

4.1 Law as a Mechanism for Economic Security

If the theoretical claim is that law stabilizes expectations, the Karabakh case illustrates how economic security is constructed through a combination of state-led reconstruction and institutional design. Since the end of the 2020 war, Azerbaijan has pursued an intensive reconstruction policy, allocating substantial public resources to infrastructure, resettlement, and economic revitalization. According to official data, more than 19 billion manats have been directed toward the restoration of Karabakh and East Zangezur between 2021 and 2024 [1] This level of investment signals not only a commitment to physical reconstruction but also an attempt to re-establish a functioning economic space.

However, the structure of these policies indicates that economic recovery is being approached as an institutional problem. The establishment of industrial zones, such as the Aghdam Industrial Park, reflects an effort to create legally defined economic environments with specific regulatory and fiscal regimes [2] These zones operate through tax incentives, customs privileges, and administrative simplifications

designed to reduce uncertainty for investors. Similarly, broader reforms in the liberated territories include preferential legal frameworks intended to attract private capital and support long-term economic activity. [15]

This approach aligns with the broader insight that in post-conflict settings, economic security depends less on the volume of investment and more on the predictability of the legal environment. Infrastructure alone cannot generate sustained economic activity if ownership rights remain unclear, contracts are weakly enforced, or regulatory frameworks lack credibility. In Karabakh, these risks are particularly pronounced. The region's prolonged separation from Azerbaijan's legal system resulted in the erosion of formal property relations and the emergence of unregulated economic practices, as documented in Hajiyeva's study of occupation-period economic activities [4].

The challenge, therefore, lies in transforming a state-driven reconstruction process into a legally grounded economic order. The return of internally displaced persons under the "Great Return" program illustrates this tension. While resettlement is progressing, its long-term success depends on the enforceability of housing and land rights, as well as the existence of functioning legal institutions capable of resolving disputes [5] Without these elements, economic recovery risks remaining dependent on continued public intervention rather than transitioning into a self-sustaining system.

4.2 Regional Integration and Trade Dimensions in Karabakh

Regional integration in Karabakh should not be reduced to transport corridors or customs flows alone. In the present phase, integration is being built through four interlocking channels: physical connectivity, productive incentives, human-capital institutions, and return-led urban reconstruction. What distinguishes Karabakh from an ordinary regional development case is that trade recovery and territorial reintegration are unfolding simultaneously. Roads, airports, industrial parks, universities, and housing complexes are not separate projects. They are components of a single state-building and market-forming process. The significance of this lies in sequencing: before Karabakh can become a competitive regional node, it must first become a governable and investable economic space [16; 17].

From the standpoint of trade and investment, the state has tried to compress that transition by combining infrastructure with unusually strong incentives for business entry. In the liberated territories, entrepreneurs benefit from a package that goes beyond ordinary tax relief. The Ministry of Economy states that, until 1 January 2033, entrepreneurs operating in these territories can access broad tax and social-insurance support; for production businesses, 20% of monthly utility costs are covered by the state, and self-employed persons operating without employees receive a 100% subsidy on mandatory social-insurance contributions for ten years [15; 16]. In the Aghdam and Araz Valley industrial parks, residents are exempt for

ten years from property, land, and profit taxes, and from VAT and customs duties on imported machinery and equipment [16].

Aghdam Industrial Park is the clearest example of how this model works in practice. The park covers 190 hectares, more than 70% of its territory has already been allocated for entrepreneurial use, and it ranks second in Azerbaijan's industrial-park system by number of resident enterprises. As of April 2025, 9 enterprises were already operating there, with outputs supplied both to the domestic market and to export markets. The green-energy agenda adds a second integration layer. Karabakh and East Zangezur have officially been framed by the Azerbaijani state as green energy zones. By May 2025, 38 hydroelectric plants with a combined capacity of 307 MW had become operational or ready for commissioning across the region, reducing energy dependency and supporting industrial activity [5]

The smart-village program serves a related function at the local level. In Aghali, the first phase of the "Smart Village" project created the first return model for village-scale resettlement after the war. A similar approach was implemented in Zabukh village, where reconstruction was directly linked to sustainable energy use and modern infrastructure planning [5;6]. Urban return is now giving this strategy demographic substance. In Shusha, the first residential complex contains 450 apartments, with the first families returning in 2024. In Aghdam, the second residential complex includes 1,268 apartments, with thousands of residents expected to relocate during 2025–2026 [6;7]. Earlier projections indicate that at least 140,000 people are expected to resettle in Karabakh and East Zangezur during the initial phase of the Great Return. In this context, Karabakh University plays a structural role in regional integration. Established in Khankendi in 2023, the university has rapidly expanded, reaching more than 2,000 students across multiple faculties [12]. Its function extends beyond education: it supports human capital formation, local economic participation, and long-term regional stabilization.

Taken together, these measures show that Karabakh's integration model is being constructed through coordinated state intervention combined with institutional development. Shusha is being rebuilt as a cultural center, Aghdam as an industrial hub, and Khankendi as an educational core. The broader implication is that regional integration in Karabakh is not only external but also internal linking previously disconnected territories into a unified economic and legal space [19].

4.3 Investment Incentives and Economic Zones

In Karabakh, investment policy has been designed not as a neutral business-support instrument but as a reconstruction tool. The state's approach is clear: reduce the entry cost of private capital in a post-conflict territory where normal market incentives would be too weak on their own. For that reason, the incentive regime in the liberated territories is broader than ordinary regional support. Until 1 January 2033, residents are granted 0% profit (income), property, land, and simplified taxes,

while imports of equipment and raw materials for relevant economic activities are exempt from VAT and customs duties. Dividend income is also tax-exempt. In addition, the state guarantees up to 90% of eligible business loans, subsidizes up to 10 percentage points of annual interest on guaranteed loans, and covers 20% of monthly utility costs for production-oriented entrepreneurs [19; 20; 21].

The economic rationale is straightforward. In a post-conflict zone, the main constraint on business formation is not only capital scarcity but risk concentration. The incentive package is therefore structured to lower fixed costs, reduce financing risk, and shorten the payback period for first movers. This matters especially for manufacturing and logistics, where entrepreneurs face high upfront costs and delayed returns. The policy is also labor-market oriented: employers' mandatory social-insurance contributions for hired workers were subsidized at 100% until 1 January 2026, then scheduled to decline gradually, while self-employed entrepreneurs without employees receive 100% social-insurance subsidization for 10 years. These measures are better understood as a transition mechanism: they are meant to compensate for the institutional and commercial disadvantages of operating in a territory still emerging from war [12; 16; 19].

Indicator	2025	2026	2027	2028
State allocation to Karabakh and East Zangezur (AZN bn)	4.0	3.5–4.0	3.0–3.7	2.8–3.5
Aghdam Industrial Park residents	29	33–36	37–42	41–48
Araz Valley Economic Zone investment portfolio (AZN million)	140–150	165–180	190–220	220–260
Population living and working in liberated territories	48,000+	58,000–65,000	70,000–82,000	85,000–100,000

Table 1.

Selected Economic Indicators for Karabakh Reconstruction (2025–2028) (Source: MoE Azerbaijan [18]–[20]; Presidential Decrees and State Programs [15]–[16]; authors' estimates)

Note: The projections for 2026–2028 are authors’ estimates derived from official reconstruction targets, announced investment commitments, and observed development trends in the liberated territories between 2021 and 2025. The figures should be interpreted as indicative projections rather than official government forecasts.

The most concrete expression of this model is the industrial-zone framework. In Aghdam Industrial Park, residents are exempt for 10 years from property, land, and profit taxes, as well as VAT and customs duties on imported machinery and equipment. By December 2024, the park had reached 29 residents; one new resident alone committed AZN 18 million, planned annual output of 144,000 tons of metal products, and 150 permanent jobs [19]. This suggests that the park is moving beyond symbolic reconstruction toward an actual production base. In Araz Valley Economic Zone Industrial Park, by July 2025 there were 18 resident business entities with a combined investment portfolio of AZN 140 million, plus 3 non-resident entrepreneurs. A new transformer-manufacturing project added roughly AZN 17 million more investment and planned annual production of 3,000 units. These figures indicate that the state is trying to build sectoral clusters rather than disperse subsidies across disconnected firms.

The broader macroeconomic frame is also important. From 2021 to the end of 2024, Azerbaijan reported allocating more than AZN 19 billion to the restoration of Karabakh and East Zangezur, while the 2025 state budget alone assigned AZN 4 billion to these territories. At the same time, the official “Great Return” platform states that industrial and specialized production zones are intended to stimulate entrepreneurship, attract investment, and accelerate reintegration into the national economy; it also reports that more than 48,000 [18].

people currently live and work in the liberated territories.¹ This means the incentive regime should be read not only as tax policy, but as a mechanism for converting budget-led reconstruction into a private-sector base. The real test, therefore, is not whether incentives attract initial residents they already have but whether these zones can generate durable production, employment, and local business linkages after the extraordinary support phase begins to taper.

4.4 Challenges and Future Legal Reforms

The reconstruction of Karabakh is often presented as a success of rapid state-led development. Roads are being built, industrial zones are operational, and population return has begun. Yet beneath this visible progress lies a more difficult question: whether the emerging economic order can sustain itself once reconstruction shifts

¹ Daniel Fitzpatrick, “Land, Custom, and the State in Post-Conflict Societies,” *World Development* 34, no. 11 (2006): 1860–1877.

from state financing to market dynamics. The challenge is not reconstruction itself, but the transition from reconstruction to normal economic governance.

The first structural challenge concerns legal certainty in property relations. Post-conflict territories rarely inherit clean legal records. In Karabakh, decades of institutional discontinuity have produced gaps in land registries, overlapping claims, and the absence of enforceable historical documentation. As Fitzpatrick argues, post-conflict land systems are often characterized by competing claims and weak institutional enforcement, which directly constrain economic recovery [1; 12]. While reconstruction projects proceed under state authority, long-term investment requires legally defensible ownership. Without a consolidated cadastre system and transparent dispute-resolution mechanisms, property remains an asset with limited liquidity.

A second challenge lies in the dependence on extraordinary incentive regimes. The current model is built on tax exemptions, subsidized utilities, and state-backed credit guarantees. These instruments are effective in attracting first movers, but they are temporary by design. The literature on post-conflict reconstruction consistently shows that externally driven or incentive-based growth is fragile unless supported by institutional consolidation. Del Castillo emphasizes that reconstruction policies must prioritize institutional stabilization; otherwise, economic gains remain reversible. In Karabakh, the key issue is therefore not the presence of incentives, but their eventual withdrawal and the system's ability to function without them [1].

A third issue concerns institutional asymmetry between the center and the region. Post-conflict governance is often centralized in the early stages, but long-term stability depends on decentralization and local institutional capacity. Lake's work on post-conflict institutions shows that localized governance structures are essential for sustaining order and reducing uncertainty at the micro level. In Karabakh, local administrative and legal institutions are still developing, and without their strengthening, economic governance risks remaining dependent on central coordination.

The labor market introduces another dimension of legal challenge. The return of internally displaced persons is not only a demographic process but a legal-economic one. Secure access to housing, employment, and economic participation depends on enforceable rights and functioning institutions. Joireman's work on post-conflict property restitution highlights that unresolved land and housing issues can undermine both return and economic stability [1; 12; 19]. In this sense, economic recovery is closely tied to the legal integration of returning populations into formal economic structures.

These challenges point toward a set of necessary legal reforms, which are less about creating new laws and more about consolidating enforceability. The first priority is the development of an integrated and transparent land and property registration system. Deininger's work demonstrates that secure property rights and reliable land administration systems are critical for investment and economic growth.

The second reform area concerns investment law stabilization. Rather than relying indefinitely on exemptions, the legal framework should gradually shift toward predictability, clear tax regimes, stable regulatory requirements, and credible enforcement institutions. This aligns with Acemoglu and Johnson's argument that long-term economic performance depends on institutions that protect property rights and limit arbitrary intervention. Third, there is a need to strengthen local legal capacity, including administrative courts and regulatory bodies. Without these, economic activity remains administratively driven rather than institutionally grounded [3;4].

The broader implication is that the future of Karabakh's economy will not be determined by the scale of reconstruction, but by the depth of its legal transformation. Infrastructure can be built rapidly; institutions cannot. The transition from a reconstruction economy to a functioning market economy depends on whether legal frameworks become credible constraints rather than temporary instruments.

Conclusion

The reconstruction of Karabakh demonstrates that post-conflict recovery cannot be understood solely as a process of physical rebuilding or financial allocation. While large-scale public investment, infrastructure development, and incentive mechanisms have accelerated economic activity, these elements remain transitional unless supported by a coherent and enforceable legal framework. The central finding of this study is that economic law is not a secondary component of reconstruction, but a constitutive condition for transforming short-term recovery into sustainable economic development.

The analysis has shown that legal certainty, particularly in property rights, investment regulation, and institutional governance plays a decisive role in reducing uncertainty and enabling economic actors to commit resources over the long term. In the absence of such certainty, even well-funded reconstruction efforts risk producing fragmented or subsidy-dependent outcomes. The case of Karabakh illustrates this dynamic clearly: state-led development has created initial economic momentum, but its durability depends on the consolidation of legal institutions capable of supporting market-based activity.

At the same time, the region reflects broader patterns identified in post-conflict scholarship. The challenges of property restitution, institutional capacity, and the gradual withdrawal of incentives are not unique, but their interaction in Karabakh creates a distinct transitional environment. The effectiveness of future reforms will therefore depend on sequencing ensuring that legal frameworks evolve in parallel with economic transformation. In this sense, the long-term success of Karabakh's reconstruction will not be measured by the scale of investment already achieved, but by the extent to which a stable, predictable, and enforceable legal-economic order can be established.

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Megatrends, circular economy business models, and sustainability regulation in business

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Abstract: The clock of the end of the world was moved forward again at the beginning of 2026. At the same time, updated megatrends and 2026 trends were published, and consideration was given to how to continue anticipating adverse factors and strengthen sustainable development measures through corporate actions. If there is no healthy planet, there is no business. On the other hand, the EU-level sustainable development directives will be relaxed, for example, through Omnibus I. Despite this, Finnish companies, for example, have incorporated sustainability factors into their strategies and are ready to continue promoting sustainability through regulatory compliance and circular-economy business models. To support this, the ImpAct project at Laurea and Haaga-Helia has designed a tool to facilitate VSME reporting. From the perspective of foresight and circular-economy business models, the Finnish SME Bioscale, for example, aims to minimize food waste in practice, thereby strengthening the planetary dimension.

Keywords: circular economy business models, sustainability, VSME, megatrends

1 Introduction

The world, our planet, is in constant change. We should be aware of the condition to which we return the planet for the next generations. The development can be estimated, e.g., using megatrends that affect behavior, demography, and businesses. After the Corporate Sustainability Reporting Directive (CSRD) was mitigated in 2025, the Voluntary Sustainability Reporting Standard for SMEs (VSME) took shape to guide companies. The wording of the regulations may be difficult for SME

representatives to understand. For this reason, the ImpAct project decided to use legal design to develop the VSME tool, a tool for SMEs to support company representatives in reporting. The discussion around sustainable business models continues to focus on circular economy business models and their productivity and profitability. Therefore, comparable examples of real businesses are also important for ideation. In this paper, we address megatrends, VSME, circular-economy business models, legal design, the results of the ImpAct project, and the Bioscale example.

2 Theoretical background

2.1 Megatrends

We live in a time where only change feels permanent. To perceive the big picture over the long term, megatrends support thinking and planning. In Finland, the last time Sitra held the megatrends publication event was in January 2026.

Megatrends describe continuity and gradual change, helping to perceive root causes and the overall picture of change, and to put together a trajectory of global change shaped by phenomena. Megatrends can be used to consider, for example, different possibilities for building the future. In Finland, the focus on megatrends focused on topics ranging from the importance of people and culture to a long-lived society, from the significance of power and politics to the transformation of the world order and the power of democracy, from the importance of nature and resources to adaptation and renewal, and from the significance of technology and the economy to the transformation of the foundations of society through the impact of artificial intelligence. By leveraging megatrends, companies can identify opportunities to build a sustainable future and maintain Earth's carrying capacity. We only have one Earth, and we must keep it habitable for future generations as well. This is influenced by the geographical and political frameworks within which we are building a sustainable future together. Sustainability and new technologies require, among other things, new expertise and new materials. The circular economy is one option within the boundary conditions to ensure resource availability. [1]

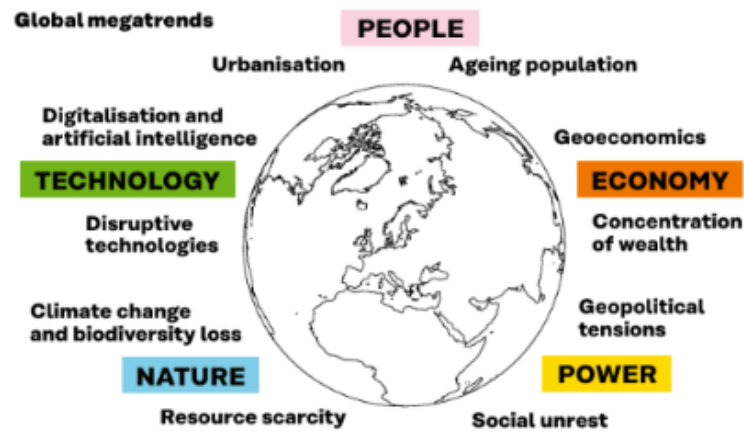


Figure 1
Global Megatrends [1].

2.2 Voluntary Sustainability Reporting Standard Framework

The purpose of the CSRD initiative was to simplify and harmonize the corporate responsibility framework and to make comparisons between companies of different sizes more comparable and easier to understand, for example, by committing companies to implementing the Green Deal and sustainable development. [2]

As the world changes, the European Commission's perspectives seek to adapt to both short- and long-term needs through directives and regulations. This can be seen, for example, in the development of the CSRD initiative into a directive, and in the issues that have supplemented or lightened it, such as Omnibus I [3], the Biodiversity Loss Regulation [4], the Ecodesign Directive [5], and the Green Claims Directive [6].

Regarding the double materiality analysis included in the CSRD relief, the reporting obligation for more than 1,000 data points would apply only to Europe's largest companies. As these smaller companies continued the sustainability measures they had begun, EFRAG developed a lighter regulatory framework, VSME, based on the new CSRD. [7]

VSME is a voluntary standard developed to support sustainability reporting by unlisted micro, small, and medium-sized enterprises, enabling them to report on the actual and likely positive and negative impacts of their business activities on people and the environment in the short, medium, and long term. In addition, it can be used to report on the actual and likely impacts of environmental and social issues on the company's position, success, and revenue stream in the short-, medium-, and long-term. [8] The information used in reporting must be appropriate, truthful,

comparable, understandable, and verifiable. In VSME reporting, the company defines the scope and content of its reporting, which it can specify and expand if it wishes. Reporting after the first year must be proportional to prior years' reporting so that changes between years are clearly visible. [9]

Regulatory frameworks, directives, and regulations can be difficult for business representatives to understand. To support the consideration and completion of these, the ImpAct project produced understandable, easily accessible tools using legal design, such as a form and a PowerPoint slide set, that can be used to address the topics from the company's perspective.

2.3 Circular economy business models

Unsustainable consumption habits combined with urbanization lead to the generation of urban waste. The circular economy can be used to produce solutions through both top-down and bottom-up activities that focus on improving the mobility of resources and information. [10] The use of circular economy business models is emerging in response to growing global sustainability concerns and resource scarcity. They serve as tools for a sustainable future, for example, by extending product shelf life and reducing reliance on non-renewable natural resources, thereby making economic development more sustainable. In addition, they can strengthen reuse, repair, refurbishment, and reduction. [11] Circular economy business models examine how to create resource-efficient life cycles in which, for example, raw materials are mined or processed in different ways and places before their end use. Each has its own life cycle, which consists of distinct stages. [12]

3 Legal Design and Sustainability Rights

Through legal design, the aim is to achieve a human-centered and participatory functioning of the legal system, for example, through visual design. Legal design, for example, improves accessibility for laypeople. Legal design can be used, for example, to solve process and usability problems by addressing people's needs and opportunities. In this way, problems can be solved quickly and comprehensively through cooperation among different parties, and as comprehensibility increases, it becomes easier to navigate the legal system. User-centered thinking in legal design offers an opportunity to prevent challenging situations.[13][14]

When discussing legal design, Corrales Compagnucci, Barton, and Haapio are associated with the principles of knowledge design and legal approaches that anticipate and prevent legal welfare issues. [13].

The design of sustainability rights involves using visualizations to facilitate and clarify the processing of sustainability data (regulations, directives, agreements, etc.), establishing clear language standards, producing data with digital tools, and incorporating design models into the company's processes and legislative drafting. The formulation of sustainability regulation includes choices and various value bases, as well as consideration of the implementation, understanding, and enforcement of laws. [15]

4 Results

After the CSRD was eased in 2025, the VSME standard took shape to guide SMEs, for example. The wording of the regulations may be difficult for SME representatives to understand. For this reason, the ImpAct project decided to use legal design to develop the VSME tool, which supports company representatives in reporting.

Biovaaka, which uses the circular economy business model, can apply, e.g., the guidelines developed by the ImpAct project to clarify sustainability regulations and support and facilitate sustainability work. The instructions were presented in a way that made the step-by-step progression of the topic more natural. Using the instruction form, the company's representative can clearly explain the company's requirements under the Sustainability Act. The starting point for the form is to consider who, which sustainability law or regulation, in what kind of situation the need arises, and why it is needed. After this basic information, we consider what happens if someone does not receive or understand the necessary law or regulation, e.g., a risk assessment is carried out. After the risk assessment, the content of the law or regulation is described in an understandable, precise, and concrete manner to meet the needs of the company's representative. This encompasses an accurate description of what each person should, must, or cannot do. The description should use appropriate, respectful language in concise sentences with familiar, precise terms for the company's personnel. If difficult terms are encountered in the topic, they should be explained clearly and, if necessary, illustrated with examples and diagrams. In the same context, a link to the original act or website must be included so that future amendments to the act can be followed. Regarding the company's internal materials, the necessary information and links are added to ensure they reach users at the right time, comply with applicable laws and regulations, and remain up to date and ready for updates. The instructions will be made comprehensible to users, and the wording will be updated as necessary.

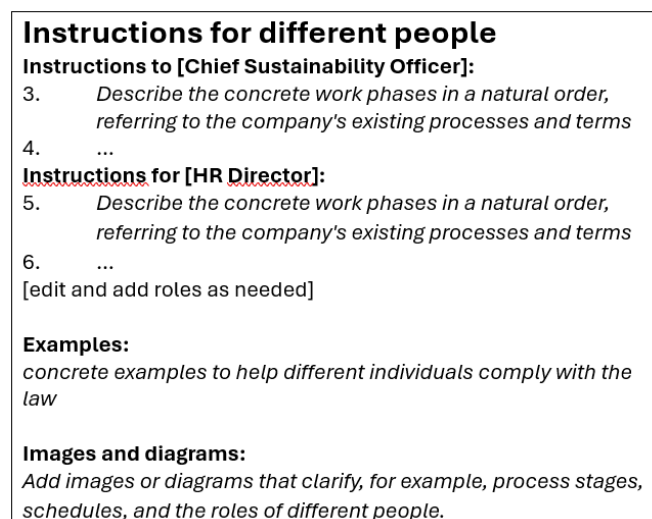


Figure 2

Example of guidelines to clarify sustainability regulations for company representatives.[16]

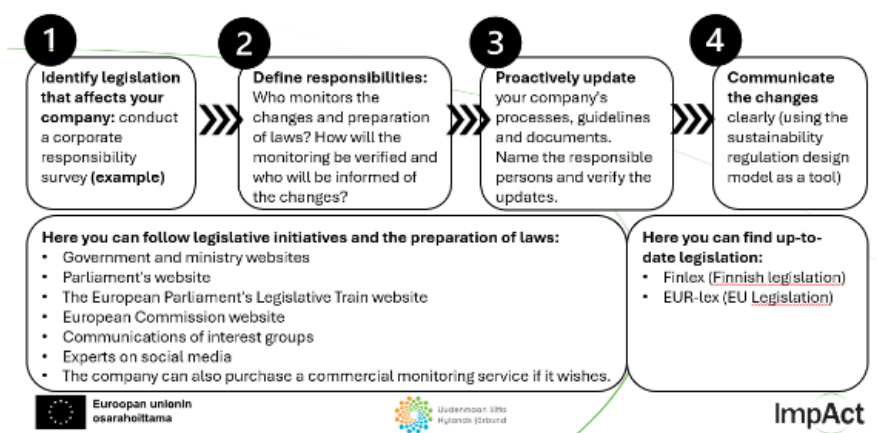


Figure 3

Template for monitoring sustainability regulation. [17]

In the ImpAct project, a sustainability reporting model for the voluntary sustainability reporting standard, published by EFRAG on 17 December 2024, was developed for SMEs, with support for legal formulation. The model, based on the EFRAG Voluntary Sustainability Reporting Standard for non-listed SMEs (VSME), included both a basic and a broader module aligned with the VSME standard's reporting items. When using the model, the document on which the model is based must be used, as the model formulated by the project does not contain all the details or instructions of the document, and it is not a model approved by

Basic module	Extensive module
Basic Information • B1 Basis for the preparation of the report • B2 Practices, policies and initiatives for the transition to a more sustainable economy	Basic Information • C1 Strategy: Business model and sustainability initiatives • C2 Practices, policies and initiatives for the transition to a more sustainable economy
Environmental indicators • B3 Energy and greenhouse gas emissions • B4 Air, water and soil pollution • B5 Biodiversity • B6 Water • B7 Circular economy	Environmental indicators • C3 Greenhouse gas emission reduction targets and climate transition • C4 Climate risks
Social metrics • B8 Workforce: Basic Information • B9 Labour force: Health and safety • B10 Labour force: Wages, collective bargaining and training	Social metrics • C5 More information about the workforce • C6 More information on the own workforce: human rights policies and processes • C7 Serious human rights impairments
Governance indicators • B11 Convictions and fines for corruption and bribery	Governance indicators • C8 Income from specific sectors and exclusion from EU benchmarks • C9 Gender distribution of the governing body



European union
osarahittama



**SECTIONS OF THE VSME DOCUMENT
WHERE YOU CAN FIND MORE
DETAILED INSTRUCTIONS**

B3 Energy and greenhouse gas emissions: Energy consumption

VSME:
29
82-89

**VSME ID AND TITLE
OF THE
INFORMATION TO
BE REPORTED**

	Renewable energy consumption (MWh)	Non-renewable energy consumption (MWh)	Total energy consumption in 20XX (MWh)
Electricity			
Fuels			
Total			

**INSTRUCTIONS ON
THE CONTENT OF
REPORTING**

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By combining reporting and circular economy business models, Biovaaka Ltd has also made the monitoring of everyday food waste a focus of circular economy business models. The company's service is based on easy, fast monitoring of food waste, with clear, comprehensive reporting. It can be targeted at different stages of the process, and, in this way, monitoring food waste provides information to support development and reduce costs. The information obtained from reporting can be used, for example, to plan food orders and production volumes. [19]

Prepared food waste is not limited to discarded ingredients. It already contains labour, planning effort, and professional competence. Energy spent on storage, cooking, and heating is lost, as is water used for preparation and cleaning. In addition, transport-related fuel consumption, logistics, and associated emissions are embedded in prepared food waste. Waste, therefore, represents the loss of accumulated value created along the supply, transport, and service chain. Recent international assessments emphasize that food waste embodies wasted labour, energy, water, transport, and added value across food systems. [20]

Conclusions

Long-term global change does not emerge from regulation alone, nor can it be achieved through isolated business actions. Instead, it requires an interaction among megatrend-based foresight, sustainability regulation, and business models to translate policy objectives into everyday practices. For small and medium-sized enterprises in particular, limited resources, time constraints, and varying levels of regulatory expertise shape how sustainability measures are understood and implemented in practice.

This study highlights the role of legal design as a practical connector between regulatory intent and operational reality. Presenting sustainability regulation in clear language, structured formats, and visually supported steps does not reduce regulatory ambition but supports implementation by making requirements interpretable and actionable. In business environments where sustainability obligations compete with daily operational priorities, clarity becomes a prerequisite for effective compliance and meaningful engagement rather than an added feature.

The case of Biovaaka Ltd. illustrates how circular economy principles can be embedded into routine business activities through feasible measurement and reporting practices at the SME level. At the same time, the findings must be interpreted in light of process-related limitations. The analysis is based on project-driven development work, a limited number of illustrative cases, and a specific regulatory phase within a national context. Rather than generalizing results across all SMEs, the study demonstrates how proportionate reporting models, supported by legal design, can help align sustainability regulation with everyday decision-making. Incremental, context-sensitive actions can thus cumulatively contribute to more sustainable and resilient business practices.

Acknowledgement

The ImpAct project provides free help for monitoring sustainability regulations and reporting for companies. It facilitates monitoring of sustainability regulations and uses legal design to make, e.g., the regulation's wording understandable. It also supports SMEs, particularly in implementing VSME and innovating sustainable

products and services based on circular-economy business models. This article was developed in collaboration with the ImpAct project.

AI tools were used to support language editing, improve clarity and readability, and check the IEEE reference list.

Declaration of Interests

Dr. Jukka Sirkiä is a board member of Biovaaka Ltd., a campus-based startup company originating from LAB University of Applied Sciences and LUT University. Biovaaka Ltd. supports restaurants and professional kitchens in reducing food waste while simultaneously improving sustainability performance and operational profitability.

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Generative AI in Higher Education: Adoption and Impact of Custom GPT Chatbots on Student Learning in Management Accounting and Finance

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Abstract: Generative AI has become an integral part of students' everyday learning. A majority of students already use commercial chatbots as support tools. Against this backdrop, Horus and FinPro were created, two Custom GPT Chatbots for teaching support in the subjects of Management Accounting and Finance at Hochschule Ruhr West (Germany). They are designed to direct students to quality-assured bots that have been specially trained in the respective topics. Initial findings show that the bots are well received – two-thirds of students now use them regularly despite already being accustomed to using commercially available chatbots. Furthermore, Horus and FinPro are utilised in a variety of ways for learning purposes, with traditional features such as answering questions being employed more frequently than options like generating exercises. In our study, the use of generative AI has surpassed classic internet research and the use of YouTube videos. However, students are also aware that the chatbot's answers cannot be trusted completely due to hallucinations and incorrect source references. Supporting students in developing a critical and reflective approach to generative AI should therefore be understood as a key responsibility of higher education teaching.

Keywords: Custom GPT Chatbots, AI-assisted learning, Student Learning Behavior, Critical Thinking, Management Accounting, Finance

1 Introduction

As a key technology of digital transformation, generative artificial intelligence (GenAI) is increasingly reshaping how teaching and learning are designed and experienced in higher education. Recent review studies show that Large Language Models (LLMs) are now being applied across a wide range of academic contexts, including tutoring, formative feedback, assessment support, content generation, and student assistance. At the same time, the literature emphasizes that their educational value is not uniform: while some studies report gains in engagement, accessibility, and learning support, others highlight important limitations, including over-reliance, uneven effectiveness across disciplines, and unresolved questions concerning pedagogical impact [1]–[3].

This debate takes place against the backdrop that GenAI has become firmly embedded in students' everyday study practices. Recent evidence from Germany shows that AI is already used frequently in higher education: 65% of surveyed students reported using AI weekly or daily in their studies [6]. The most common purposes include general research and gaining an overview of a topic, brainstorming, using AI as a learning partner or tutor, and translation [6, 7]. At the same time, usage patterns differ across disciplines, indicating that AI adoption is now widespread but still shaped by subject-specific learning cultures [6]. Beyond the German context, current international evidence likewise points to very high levels of adoption, with more than 90% of respondents in a recent university study reporting that they use AI to support academic activities [8]. Together, these findings suggest that the use of GenAI is no longer a marginal phenomenon, but a structural feature of contemporary student learning [6], [8], [9].

At the same time, recent studies indicate that institutional support has not yet fully caught up with students' rapid uptake of these tools. In the German CHE survey, students rated their university's existing provision for acquiring AI-related competencies at only 2.7 out of 5 on average [6]. They also expressed strong expectations regarding clearer ethical guidelines, data protection, and more systematic learning opportunities for AI literacy [6]. This suggests that higher education institutions are under growing pressure not only to regulate AI use, but also to integrate it pedagogically in ways that are transparent, discipline-sensitive, and educationally meaningful [6]. Closely linked to this is the question of whether GenAI is ultimately helpful or harmful for student learning [10, 11]. Research on self-regulated learning (SRL), understood as learners' active regulation of goals, strategies, motivation, and reflection throughout the learning process, shows that students vary considerably in how strategically and critically they use AI tools:

some employ AI in ways that support deeper engagement and metacognitive regulation, whereas others rely on it more superficially or uncritically [12, 13, 14]. Current evidence therefore points less to a simple positive-or-negative assessment than to the importance of usage quality, strategic awareness, and pedagogical framing [12]. In particular, recent work argues that higher education should foster students' metacognitive and ethical awareness in AI-supported learning and cultivate forms of use that promote reflection rather than shortcut thinking [12, 13]. A systematic review of AI applications in supporting SRL confirms that while AI tools can facilitate all three phases of the SRL cycle – forethought, performance, and self-reflection – their impact remains uneven across phases, with the performance phase receiving the most support. The review further cautions that over-reliance on AI-generated guidance can undermine learners' autonomous regulation and self-efficacy if not accompanied by deliberate pedagogical framing [14]. Overall, reviews of ChatGPT and related systems conclude that GenAI can provide substantial benefits for feedback, explanation, and academic support, but only when embedded in clearly structured educational settings and accompanied by critical guidance [1]. This underlines the need for institutionally supported, course-aligned AI applications that do not merely offer technical convenience, but contribute to academically sound and pedagogically responsible learning processes [12], [1], [13].

Within this broader landscape, virtual assistants based on LLMs have emerged as a particularly relevant application area for course-aligned learning support. Current evidence suggests that such systems can support individualized learning by providing immediate explanations, adaptive responses, and dialogue-based assistance tailored to learners' needs [1], [2], [4]. Importantly, the educational potential of these assistants increases when they are not deployed as generic chatbots, but are embedded in course-specific environments and linked to curated instructional materials [1], [5]. A key enabling concept in this context is Retrieval-Augmented Generation (RAG), which improves factual grounding and contextual relevance by connecting the model to an external knowledge base [5]. Accordingly, RAG is widely regarded as a promising architecture for educational applications, especially when assistants are grounded in course materials rather than relying solely on the model's general knowledge [4], [5]. At the same time, the literature identifies important limitations, including hallucinations, incomplete retrieval, outdated source material, and limited multimodal capabilities [5, 15]. These challenges are particularly relevant in higher education, where students require not only quick answers, but also reliable, transparent, and pedagogically appropriate support [1], [2], [4].

Empirical work on virtual teaching assistants further points to promising results under these conditions. A large-scale real-world evaluation of an LLM-based virtual teaching assistant found that such systems can provide instant support at scale, facilitate multi-turn interaction, and complement traditional instructor–student communication patterns [4]. However, student acceptance and educational value

depended strongly on perceived usefulness, response quality, and the extent to which the assistant was aligned with the learning context [4], underscoring that success is shaped not only by technical performance, but also by didactic design and institutional integration [1], [4]. A prominent example of a virtual teaching assistant ecosystem is ETHEL, developed at ETH Zurich. ETHEL has been used across multiple semesters and comprises several production-ready tools, including a reference-based chatbot, homework feedback, and short polling functions [16]. Further research shows that ETHEL serves as a platform for extending conversational support into additional learning functions, such as the generation of validated practice problems on demand [17]. In parallel, work on AI-supported grading in physics demonstrates that LLM-based assessment systems can reach a comparatively high level of agreement with human grading while still requiring human oversight, especially in high-stakes contexts [18]. Taken together, these findings indicate that virtual assistants can provide pedagogically valuable support when instructional control remains with the instructor and the AI system is confined to clearly defined educational functions [16]–[18]. In summary, recent research suggests that GenAI-based virtual assistants can become a meaningful component of higher education teaching when they are grounded in course materials, embedded in clear pedagogical structures, and accompanied by ongoing human oversight – a principle that appears highly transferable to other applied subject areas, including management accounting and finance [1], [5], [16].

Against this background, the present paper focuses on virtual learning assistants in the fields of management accounting and finance. The aim is to show how AI-supported assistants can provide academically sound, evidence-based, and didactically meaningful support when they are embedded in a clearly defined course context and constrained by an approved source base. More specifically, the paper presents the conception, implementation, and evaluation of the two pilot projects HORUS and FinPro at Ruhr West University of Applied Sciences. Both assistants were designed to support students in a dialogue-based manner, guide them in working with subject-specific materials, and provide structured assistance in understanding concepts and solving course-related tasks. This paper therefore contributes to the current debate on how GenAI can be integrated into higher education not merely as a general-purpose tool, but as a course-aligned learning support system with clear pedagogical guidance and boundaries [1], [4], [5].

2 Methods

2.1 Conceptual Design of HORUS and FinPro

HORUS and FinPro are so-called custom GPTs, that is, specially configured versions of ChatGPT that can be tailored to particular target groups or tasks without requiring programming skills [19], [20], [21]. In this process, instructors define the assistant's behavior through simple natural-language instructions ("custom instructions") and upload course-relevant materials such as PDF documents, which the system can draw upon when answering questions [20]. The objective is to provide learners with academically sound and comprehensible support, with a particular emphasis on reliable information provision and transparent source citation. This makes it possible to control the model's behavior precisely with regard to language style, technical terminology, and response strategy [20].

Technically, HORUS and FinPro are – like ETHEL – based on a Retrieval-Augmented Generation (RAG) approach that enables answers to be generated exclusively on the basis of predefined sources [5]. The materials used stem from the Management Accounting and Finance modules at Ruhr West University of Applied Sciences, which have been taught in a flipped-classroom format since 2020. A broad range of documents is therefore available, including lecture notes, exercise materials with solutions, as well as instructional videos and recorded lectures by the instructors. For HORUS and FinPro, these audiovisual materials were transcribed with AI support using the OpenAI tool Whisper and stored as structured text in PDF format. HORUS and FinPro answer only those questions that can clearly be assigned to the subject areas of Management Accounting and Finance. They are instructed not to draw on their own inferences or on sources outside the predefined set. In addition, HORUS uses selected authorized external sources, such as the Controlling-Wiki, the ControllingPortal, and specialist articles that are likewise made available in the Moodle course environment. Independent inferences or external data are explicitly excluded in order to ensure content reliability.

Unlike ETHEL, no university-owned server infrastructure is available. The system therefore runs through a standard ChatGPT Plus account. Students access HORUS and FinPro via a link provided in the Moodle course environment.

The custom GPT instructs HORUS and FinPro to include a source reference with every answer, either by indicating the name of the PDF used, including the relevant page number, or by providing the URL of one of the approved websites. The PDFs constitute the primary source of information. If no relevant information can be found there, an additional search of the authorized websites is carried out automatically and without any further action required on the part of the users.

If a question can be answered neither from the PDFs nor from the approved websites, or if it does not fall within the thematic scope of Management Accounting

or Finance, the GPT is instructed to inform students politely. According to its configuration, responses are factual, precise, and easy to understand, and they are intended to support clear and structured knowledge transfer for students. Complex content is simplified where necessary. The consistency of source references and response structure, both in terms of content and form, is defined as mandatory within the custom GPT configuration [20].

The system serves several didactic and technical purposes. It answers subject-specific questions automatically on the basis of the provided materials, generates standardized source references including page numbers, for example “script page: X; source: Y,” and restricts the scope of answers to course-related content. New documents can be added easily and integrated systematically, with each source being referenced automatically [20]. In addition, HORUS and FinPro are capable of generating practice tasks and even reviewing students’ handwritten solutions. HORUS can furthermore be extended with functions such as web search, data analysis, or code interpretation, which offers particular advantages for academic advising, research-oriented work, or data-based analytical tasks [20], [22]. To illustrate Fig. 1 shows the start page of HORUS.

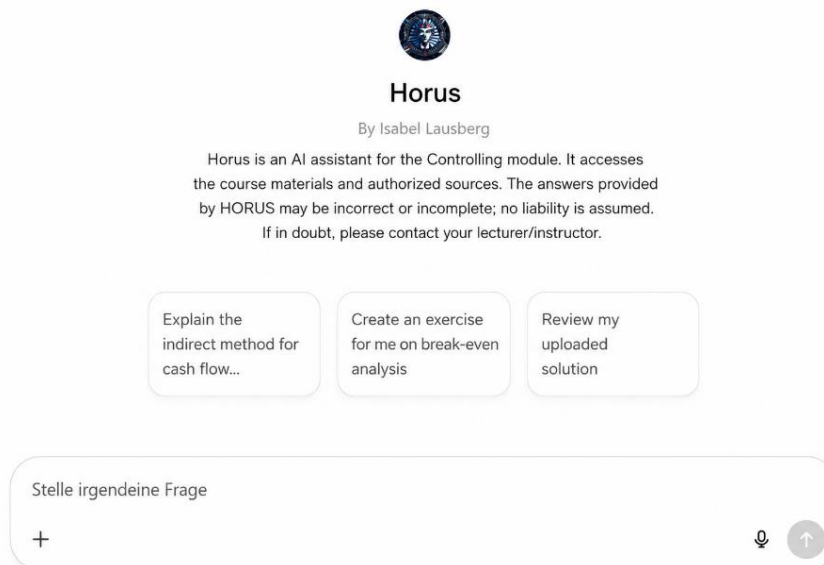


Figure 1
Start page of HORUS, Source: own edition

Similar in design to HORUS, Fig. 2 shows the FinPro start page. Here, too, following a brief introduction to the learning assistant, there are three suggested starting questions to help users get started.

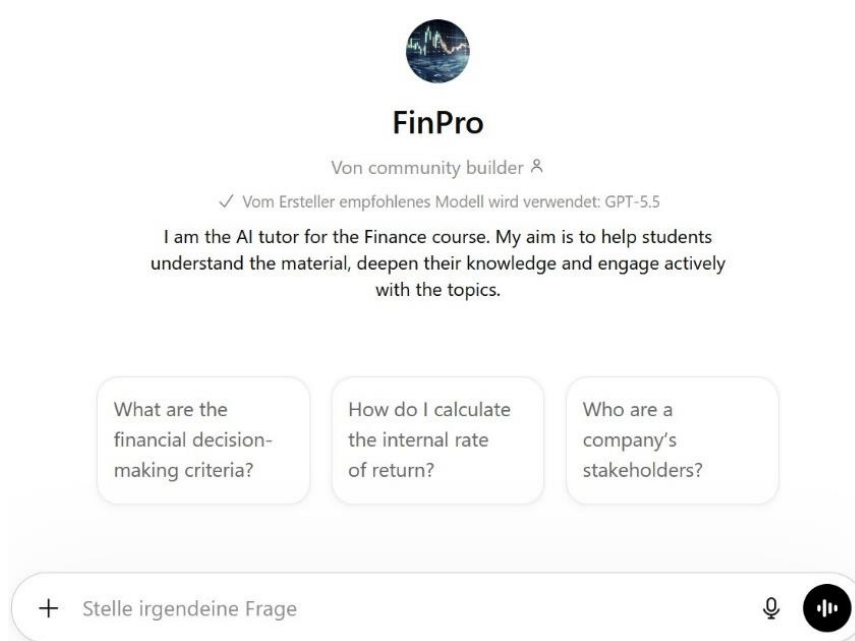


Figure 2

Start page of FinPro, Source: own edition

During development, extensive tests were conducted in order to examine the functionality and reliability of HORUS and FinPro. These included verifying correct citation behavior, testing responses to questions outside the disciplinary scope, integrating new documents, and analyzing potential sources of error. During the test phase, several PDFs were used in order to broaden the information base and simulate typical usage scenarios. Additional functions such as code interpretation and internet search were activated selectively in order to represent more complex use cases in the field of management accounting.

Overall, HORUS and FinPro represent specifically tailored AI applications which, through their combination of clearly defined content boundaries, technical extensibility, and didactic controllability, provide effective support for teaching and learning in the fields of management accounting and finance.

2.2 Survey Design and Analysis

After HORUS and FinPro had been introduced to the students as part of their respective courses, a survey was designed to evaluate the actual frequency of use, patterns of use, and students' perceived reliability of the virtual assistants HORUS and FinPro. The survey period extended from 22 January to 10 April 2026 and

comprised 29 main questions, in addition to items on basic demographic and study-related characteristics such as age, gender, and number of examination attempts. These background variables, however, are not central to the findings reported here. The survey sample comprised $n = 127$ students enrolled in the Management Accounting and Finance courses.

3 Results

One of the key questions in the survey was: “How often do participants use AI tools for learning purposes?” As noted in the introduction, recent studies indicate that the huge majority of students in Germany and abroad use AI applications [6], [7]. The current survey on HORUS and FinPro shows an even higher level of adoption: 98% of participants stated that they use AI tools for learning purposes.

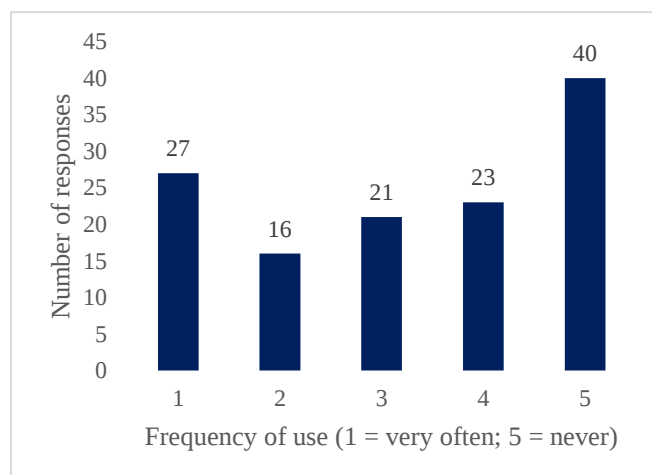


Figure 3

Frequency of use of the virtual assistants HORUS and FinPro ($n = 127$), Source: own data and edition

In addition, 69% reported that they use the course-specific AI assistants. As Fig. 3 depicts, the frequency distribution among those who use the module chatbot is relatively even. Around 21% of students (27 participants) report that they use the respective module chatbot “very often.” By contrast, 32% of students state that they “never” use the module chatbot. The most frequently cited reasons for non-use are, above all, the use of a general-purpose chatbot (17 responses) and “I have not gotten around to it yet” (7 responses).

Another survey item, illustrated in Fig. 4, aimed to examine how important the use of the course-specific AI assistants is in comparison with other learning resources (“How central is the use of generative AI compared with traditional learning aids and tools?”). The results indicate a moderate level of importance for the AI assistants HORUS and FinPro. On average, the most frequently used learning resources are the exercise script and the instructional videos available in the Moodle course environment (vodcasts / recorded lectures). General-purpose chatbots are used more frequently than the chatbot assigned to the respective module (HORUS or FinPro). However, it is remarkable that the use of generative AI has already surpassed classic internet research and the use of YouTube videos.

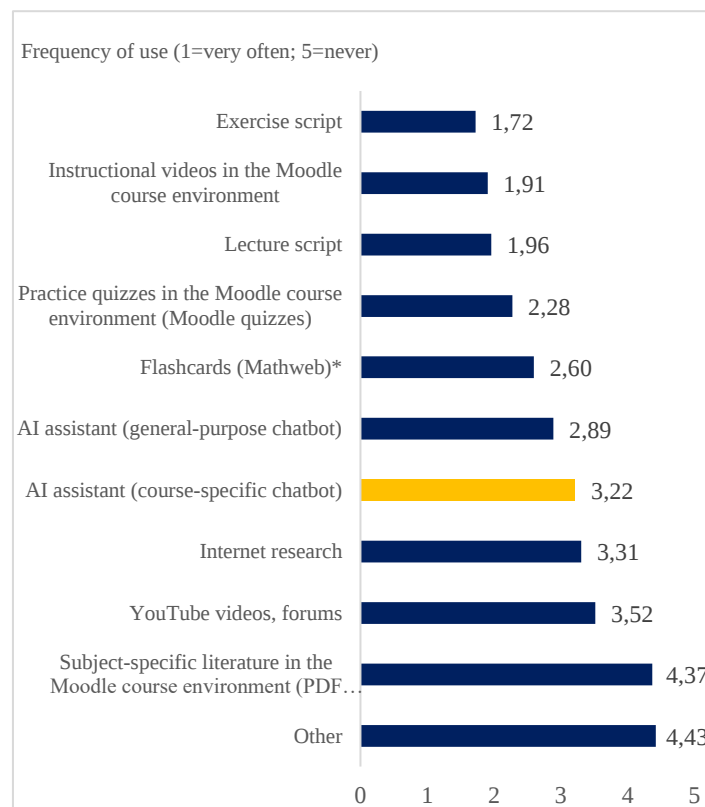


Figure 4
Use of different learning materials (arithmetic mean) (n = 127), Source: own data and edition

The least frequently used category was other learning materials (4.43). This category included, for example, mock exams, support from students in higher semesters, self-prepared summaries based on the available learning materials, and practice exercises from additional sources. As no predefined response options were

provided for this category, its lower weight is likely due at least in part to this open format. In substantive terms, however, some of these resources – particularly mock exams – are likely to be of greater importance than the overall mean value may suggest.

Furthermore, the survey examined the purposes for which the course-specific chatbots were used. For this purpose, three categories were distinguished: clarification of subject-specific questions, review of students' own solutions, and generation of additional practice tasks. The results, which can be seen in Fig. 5, show that the classic question-and-answer function is used most frequently, although it is followed closely by the upload of students' own solutions combined with requests for feedback or correction. The generation of additional practice tasks is used somewhat less frequently.

Twenty-two students reported that they had also used the course-specific chatbot for other application areas. These included using it as an active sparring partner that quizzes students on specific topics, support in solving randomized online math problems (Mathweb), as well as providing explanations and summaries ("flashcards").

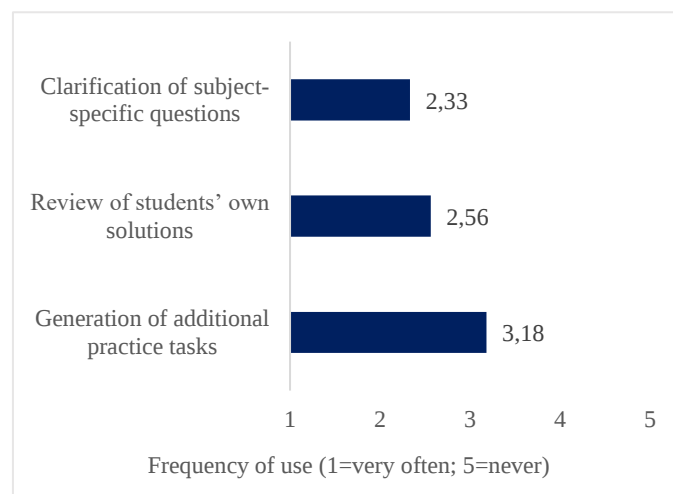


Figure 5
Frequency of use of the course-specific chatbot by application area (arithmetic mean) (n = 87)²,
Source: own data and edition

² The following figures include only responses of participants who had previously indicated that they use the respective course-specific chatbot.

While 63 out of 83 students stated that they did not wish for any additional chatbot functions, 20 respondents indicated that they would welcome further features. These include the generation of additional learning materials by the respective chatbot, for example in the form of flashcards and podcasts, the expansion of the source base to include, for instance, subject-specific literature, and the generation of tasks at examination level.

After examining frequency of use, intensity of use, and patterns of use, a further section of the survey addressed the extent to which the responses provided by the respective chatbot were perceived as reliable. As can be seen in Fig. 6, 16 students resp. 19% of participants answered the question “How often do you perceive the chatbot’s statements to be incorrect?” with “often” or “very often.”

According to the students, the most frequently reported errors concerned incorrect calculation results in quantitative tasks. Respondents also noted that the chatbot sometimes had difficulties reading and reproducing formulas correctly and that its outputs did not always correspond exactly to the lecture script. More broadly, RAG-based systems have been shown to improve factual grounding through external evidence retrieval, yet residual hallucination risks persist even in well-configured architectures [15]. This is consistent with recent findings suggesting that chatbots tend to process HTML-based content more reliably than PDF documents and are more prone to errors when working with the latter [23].

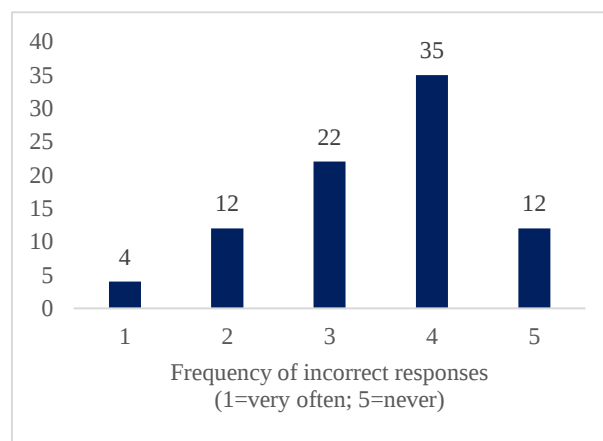


Figure 6:
In your perception, how often are the chatbot’s responses incorrect? (n = 85), Source: own data and edition

According to 66 out of 78 students, the respective chatbot generally refers to the correct source or sources. Fig. 7 below illustrates how often, in the students’ assessment, the course-specific chatbot cites sources incorrectly. Only the responses

of participants who answered “No” to the question “Are sources cited correctly?” were taken into account (12 out of 78). Only one respondent stated that the chatbot “very frequently” provides incorrect source references.

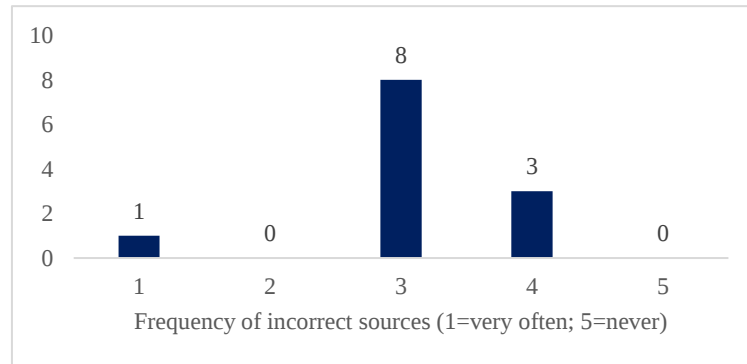


Figure 7

How often are the cited sources incorrect? (n = 12), Source: own data and edition

The majority of survey participants (73%) stated that, in their perception, the respective chatbot does not tend to hallucinate. Nevertheless, as shown in Fig. 8, 21 out of 79 students answered “Yes” to the question: “In your perception, does the chatbot tend to hallucinate, that is, to invent information not contained in the sources?”

Combined with the findings in Fig. 7 it shows that students are aware that the chatbot's answers cannot be trusted completely.

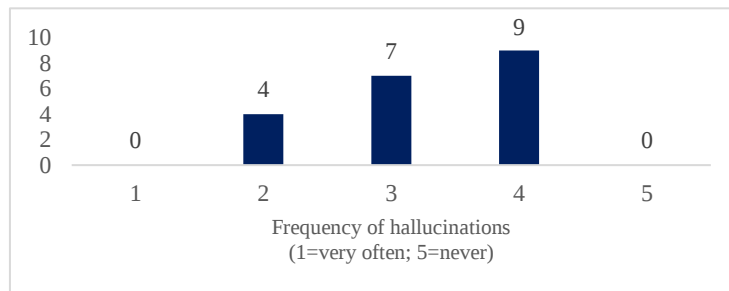


Figure 8

Frequency of hallucinations (n = 20)³, Source: own data and edition

³ Figure 8 includes only the responses of those participants who answered “Yes.” One response was excluded because, despite answering “Yes,” the respondent selected the category “never” (5), resulting in a final subsample of $n = 20$.

The students' self-efficacy in relation to chatbots was assessed on the basis of three predefined statements. On average, students feel confident using AI assistants, see added value in their learning, and trust them, although the latter point is only valid to a limited extent as can be derived from Fig. 9.

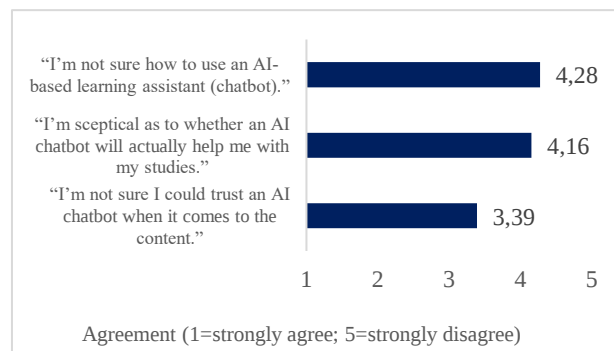


Figure 9

Self-efficacy and barriers to learning (arithmetic mean) (n = 127), Source: own data and edition

Discussions

This paper presented the design and initial evaluation of HORUS and FinPro as two course-specific, RAG-based virtual learning assistants for management accounting and finance. The findings suggest that generative AI has become a structural element of students' study practices. The survey results show both very high overall adoption of AI tools and substantial uptake of the course-specific assistants.

The overall AI adoption rate of 98% notably exceeds levels reported in comparable surveys [6]. This difference may partly reflect the effect of explicit course-level AI integration. Students primarily used HORUS and FinPro for subject-specific questions and feedback on their own solutions, whereas the generation of additional practice tasks played a secondary role. Although students perceived the assistants as useful and the source references as mostly correct, reported errors in calculations, formula handling, and occasional hallucinations indicate that course grounding improves reliability but does not fully guarantee it.

Overall, the findings suggest that course-specific virtual assistants can provide scalable and pedagogically meaningful learning support when embedded in a clearly defined course context and accompanied by explicit guidance on verification, critical evaluation, and reflective use. At the same time, the study is limited by its reliance on self-reported perceptions from a single institutional setting and by the absence of direct measures of actual learning outcomes. Initial longitudinal evidence from the German higher education context suggests that the relationship between AI tool use and domain-specific reasoning performance is

complex and requires careful empirical examination [24]. Future research should therefore examine how course-specific AI assistants can be didactically integrated in meaningful ways and how they affect SRL and learning performance.

Building on these results, the next step for HORUS and FinPro is to scale the approach by transitioning from a pilot setting to a university-wide implementation. This requires not only technical expansion but also organizational alignment to ensure consistent quality, governance, and sustainable adoption across faculties and degree programs. In parallel, continued tool development is needed to enhance system effectiveness and user experience. Key priorities include greater personalization, improved reliability through refined custom instructions, reduced errors, incorrect citations, and hallucinations, as well as the testing and integration of additional AI tools that extend functionality.

Beyond scaling and robustness, a central objective is to integrate the virtual learning assistants more deeply into the teaching and learning process. Rather than remaining supplemental tools, they should be embedded more systematically into course design so that their use becomes pedagogically purposeful. In particular, they can support individualized and self-regulated learning by providing adaptive guidance, timely feedback, and structured learning prompts, such as goal-setting prompts, progress monitoring, and reflection cues, that foster planning, monitoring, and reflection [25]. This is especially relevant because current evidence suggests that AI tools primarily support the performance phase of the SRL cycle, while their contribution to planning and self-reflection remains comparatively underdeveloped [14]. Accordingly, future development and research should explicitly examine whether and how course-specific assistants can strengthen these under-supported SRL phases through the implementation and evaluation of SRL-oriented design features.

At the same time, integration should explicitly promote AI literacy by making students' interactions with AI an object of learning. This can be achieved, for example, through guided prompt practices, critical evaluation of AI outputs, and transparency about limitations, bias, and appropriate academic use. Initial approaches to implementing such activities with groups of students have already been tested and appear promising. Taken together, responsible institutional scaling, deeper didactic embedding, SRL-oriented design, AI literacy integration, and continuous technical improvement can help increase both the educational impact and the scalability of course-specific virtual learning assistants.

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Learning Attitudes and Voluntary Engagement among Mothers Recently Returning to the Labour Market

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Abstract: While the employment rate of Hungarian mothers is increasing, they still face several difficulties and forms of maternity bias during the reboarding period. Maternity leave is frequently perceived primarily as a career break. This study is part of a broader, multi-phase research project that uses a mixed-methods approach to examine the human, social, and psychological capital of first-time returner mothers, focusing on the development during maternity leave. This exploratory study investigates learning attitudes, self-development activities, and voluntary engagement during maternity leave among mothers who have recently returned to the labour market. The findings reveal that most of the mothers engaged in some form of learning or self-development, ranging from formal courses to informal activities. Additionally, using three survey questions and K-means clustering, two distinct attitudinal profiles related to learning were identified, following the methodology of Bencsik and Juhász (2014). While causality cannot be inferred, the analysis indicates that a positive attitude towards learning is associated with higher levels of voluntary and development-oriented activity. The results provide preliminary evidence that maternity leave can be a

period of development across a wide range of areas, with learning and voluntary activities representing an underutilised resource for mothers returning to the workforce.

Keywords: maternity leave, development, voluntary engagement, learning attitudes, return to work

1 Introduction

The employment rate of Hungarian mothers has increased steadily in recent years [1], reflecting broader labour market trends and demographic changes. Despite this positive development, mothers continue to face substantial challenges when returning to work after maternity leave [2], [3]. Previous research highlights that mothers re-entering the labour market often encounter structural barriers, organisational constraints, and forms of maternity bias, positioning them as a potentially disadvantaged group of employees [4]. The results of The Human Side by UNICEF and Profession [5] further demonstrates that both employers and employees perceive the reintegration process as complex, even though employers consider the reintegration of returning mothers easier than onboarding recent graduates.

In the Hungarian context, maternity leave is particularly long compared to other European Union member states, allowing parents to remain at home with their child for a relatively long time [6]. In this paper, maternity leave refers to the entire period during which mothers are absent from paid employment due to childcare responsibilities. According to recent findings, a significant proportion of mothers return to work only after a longer absence, with 75% resuming employment more than 1,5 years after childbirth [5]. This extended interruption is typically interpreted by employers as a career break, defined as a period of time away from paid work [7].

Career breaks, particularly those associated with motherhood, are often linked to negative career outcomes and perceived disadvantages [7]. In Western organisational cultures, linear, uninterrupted career trajectories are still implicitly expected, and deviations from this pattern may signal reduced commitment or competence [8]. However, empirical evidence suggests that such linear career paths are increasingly rare, especially among women [9], [10], [11]. The social stigma surrounding career interruptions persists, often reinforcing stereotypes and contributing to long-term inequalities [12]. At the same time, emerging research emphasises that career breaks can generate value, support skill development, and contribute positively to professional trajectories when appropriately managed [5], [13].

This perspective aligns closely with human capital theory, which conceptualises individuals' knowledge, skills, and competencies as key economic resources[14]. Human capital is not limited to formal education but also includes informal learning, work-related experiences, and the development of transferable skills acquired outside traditional employment contexts. From this perspective, maternity leave may represent not only a period of absence but also an opportunity to accumulate and transform human capital through self-directed learning, training, and experiential activities.

Despite the growing relevance of this perspective, research focusing specifically on mothers' knowledge development and self-improvement during maternity leave remains limited. While earlier Hungarian studies have examined preparation for returning to work and highlighted the importance of knowledge transfer [6], [15], less attention has been paid to how mothers actively engage in learning and development during their time at home.

In addition to formal and informal learning, voluntary work represents another important form of skill development and human capital accumulation. According to the definition of the Hungarian Central Statistical Office [16], voluntary work is defined as an activity that is (i) carried out directly or through an organisation, (ii) performed voluntarily, without payment or compensation, and (iii) conducted for the benefit of individuals outside one's household or for the wider society. Such activities may contribute to the development of transferable skills, social competencies, and work-related experience, which can support later labour market reintegration.

Against this background, the present paper—part of a broader mixed-methods research project—focuses on maternity leave as a potential period of development. It examines Hungarian mothers' learning attitudes alongside their engagement in learning, self-development, and voluntary activities during their time at home. In particular, the study explores how different attitudinal profiles are associated with participation in training and voluntary work, and how these activities may contribute to the development of human capital. By doing so, the paper highlights the potential of recognising and leveraging these experiences as valuable forms of human capital, both for individuals and for organisations, to support effective labour market reintegration.

2 Data and Methodology

This paper is part of a broader, ongoing, multi-phase research project with the presented research design (Figure 1). This exploratory research uses a mixed-methods approach to examine the human, social, and psychological capital of first-time returner mothers, focusing on development during maternity leave. The target

group of the research is first-time returning employed mothers who have returned to work in the last two years. A questionnaire serves as an application form for the research and collects information about participants' backgrounds, work, learning, and voluntary work experiences, as well as social, psychological, and a few aspects of human capital. In the second step, 29 leadership skills (such as time management, stakeholder management, feedback skills, etc.) are measured through the FLIGBY serious game, providing a wider picture of mothers' human capital after an online meeting [17]. Finally, We interview the participants. The basis of the interviews is the skill profile generated by FLIGBY and mothers' perceived development during maternity leave.

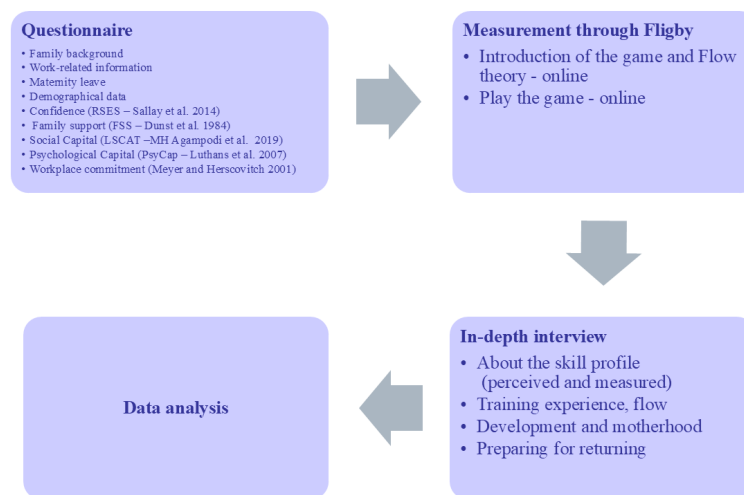


Figure 1
Research design
Source: Own Illustration

The current study examines questionnaire data collected between September 2025 and February 2026 from 41 Hungarian mothers in the target group with the presented characteristics (Table 1) regarding self-development activities, voluntary engagement and learning attitudes. Data were evaluated by SPSS 30.0.0.

	Minimum	Maximum	Mean	Std. Deviation
Age (year)	28	46	35,8	4,585
Length of maternity leave (year)	0,4	10	3,88	2,419
Work experience since returning (month)	1	24	12,95	8,5
Number of children	1	4	1,9	0,944

Table 1
Descriptive characteristics of the respondents
Source: Own Editing

The first part of the analysis presents descriptive statistics on self-development and voluntary work, using frequency counts and cross-tabulations. The second part consists of a K-means clustering analysis to identify homogeneous segments within the sample based on statements related to learning attitude. For this purpose, three survey questions on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) were used, based on the research by Bencsik and Juhász[15].

3 Results

3.1 Self-development

According to the descriptive analysis, 61% of the respondents engaged in formal or informal courses or self-development during maternity leave. Figure 2 summarises these trainings based on the 41 responses to a multiple-choice survey question. Most respondents participated in a course or expanded their professional knowledge in their field. Apart from professional development, mothers opted for language learning and personal development training to improve themselves. Furthermore, on average, respondents participated in about two types of training activities.

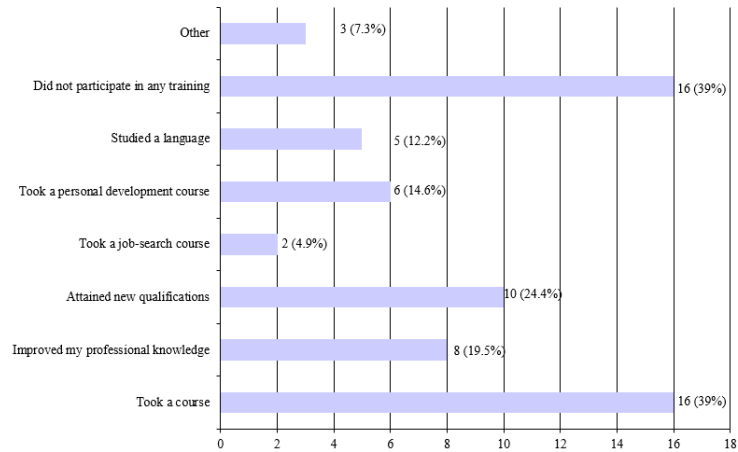


Figure 2
Trainings during maternity leave
Source: Own Illustration

3.2 Voluntary Engagement

The collected data shows that 31,7% of the respondents volunteered during maternity leave. Additionally, those who volunteered spent on average 3,7 hours per week with the chosen engagement in the year before reboarding. Furthermore, the cross-table calculation (Table 2) suggests that mothers who engaged in learning or self-development activities were substantially more likely to participate in voluntary work during maternity leave, suggesting that these behaviours may reflect a broader development-oriented attitude. Among voluntary workers, 92,3% participated in self-development activities, while among those who did not engage in self-development, 93,8% also did not participate in voluntary work during maternity leave. The result is statistically significant (Fisher's Exact Test $p = 0,006$) with a relatively strong effect size (Phi $\phi = 0,438$). Due to low cell frequencies, Fisher's Exact Test was applied.

			Voluntary work		Total
			Yes	No	
Training	Yes	Count	12	13	25
		% within Training	48,0%	52,0%	100,0%
		% within Voluntary work	92,3%	46,4%	61,0%
		% of Total	29,3%	31,7%	61,0%
	No	Count	1	15	16
		% within Training	6,3%	93,8%	100,0%
		% within Voluntary work	7,7%	53,6%	39,0%
		% of Total	2,4%	36,6%	39,0%
Total		Count	13	28	41
		% within Training	31,7%	68,3%	100,0%
		% within Voluntary work	100,0%	100,0%	100,0%
		% of Total	31,7%	68,3%	100,0%

Table 2
Cross-tabulation analysis regarding trainings and voluntary work during maternity leave
Source: Own Editing

3.3 Learning attitudes

The analysis of the three survey questions regarding learning attitudes (Table 3) suggests that participating mothers neither agree nor disagree with all the statements on average. Accordingly, mothers need to take care of their development during maternity leave to ensure successful reboarding, and young children may hinder the efficiency of studying. This result is close to the findings of Bencsik and Juhász, who reported 3,57 and 3,12, and 2,19 means for these statements in their larger sample twelve years ago.

Survey questions/statements	Mean	Std. Deviation
For a mother to successfully return to the workforce, she needs to continue developing her skills even during the time she spends at home	3,10	1,179
For a mother to successfully work again after returning, she needs to pursue self-development independently as well	2,83	1,181
If a woman has a young child, she cannot study effectively.	2,76	1,113

Table 3
Means related to learning attitudes (1 = strongly disagree, 5 = strongly agree)
Source: Own Editing

To obtain a more complex picture, Bencsik and Juhász segmented their sample into two clusters using a non-hierarchical clustering method. We were also curious about this segmentation in our sample, which is why the same procedure was conducted. The interpretation of the clusters is based on the cluster centroids. Table 4 below presents the final cluster centres obtained through the clustering procedure.

Final Cluster Centers		
	Cluster	
	1	2
For a mother to successfully return to the workforce, she needs to continue developing her skills even during the time she spends at home	2	4
For a mother to successfully work again after returning, she needs to pursue self-development independently as well	2	4
If a woman has a young child, she cannot study effectively.	3	2
Number of cases in each Cluster	23	18

Table 4
Cluster Centers
Source: Own Editing

Cluster 2 can be characterised as a development-oriented group with a positive attitude towards learning and self-improvement, while Cluster 1 represents a more constraint-oriented or less engaged group, showing lower levels of agreement with the importance and feasibility of learning during this life stage. Women in Cluster

2 do not perceive young children as a barrier to learning, whereas mothers in Cluster 1 are more likely to agree that having children negatively affects learning effectiveness.

The relatively small sample size may raise concerns about clustering. Given the limited number of clustering variables ($m = 3$) and the theoretically grounded item selection based on prior research [15], the sample size ($N = 41$) meets commonly cited minimum requirements for cluster analysis ($N \geq 2^m$) [18]. Additionally, the resulting clusters are considered interpretable within an exploratory framework.

In subsequent steps, we explored other characteristics of the clusters using cross-tabulation with two variables not included in the clustering process. The first analysis examined the relationship between clusters and participation in training or self-development during maternity leave (Table 5). Although almost twice as many respondents who did not participate in any training belong to Cluster 1 as Cluster 2, this result is not statistically significant (Fisher's Exact Test $p = 0,218$). The small sample size may yield an insignificant result; hence, it needs to be repeated in a larger sample.

			Trainings		Total
			Yes	No	
Cluster Number of Case	1	Count	12	11	23
		% within Cluster Number of Case	52,2%	47,8%	100,0%
	2	Count	13	5	18
		% within Cluster Number of Case	72,2%	27,8%	100,0%
Total		Count	25	16	41
		% within Cluster Number of Case	61,0%	39,0%	100,0%

Table 5
Participation in trainings
Source: Own Editing

On the other hand, in the second cross-tab analysis (Table 6), we discovered a statistically significant relationship between voluntary engagement and clusters (Fisher's Exact Test, $p = 0,006$), with a relatively strong effect size (Phi, $\phi = -0,453$). Accordingly, mothers in the less engaged group regarding learning (Cluster 1) are less likely to participate in any voluntary activities during maternity leave. 87% of these mothers did not volunteer as stay-at-home moms. However, half of the mothers with a positive attitude towards learning (Cluster 2) engaged in voluntary work. In other words, mothers with a less positive attitude towards learning and self-improvement are more likely to reject other forms of development during maternity leave, such as voluntary engagement.

			Voluntary work		Total
			Yes	No	
Cluster Number of Case	1	Count	3	20	23
		% within Cluster Number of Case	13,0%	87,0%	100,0%
	2	Count	10	8	18
		% within Cluster Number of Case	55,6%	44,4%	100,0%
Total		Count	13	28	41
		% within Cluster Number of Case	31,7%	68,3%	100,0%

Table 6
Voluntary work engagement
Source: Own Editing

4 Discussion

The findings of this study support a shift in perspective from maternity leave as a career interruption to a potential period of development. Rather than representing a

passive phase, the results indicate that many mothers actively engage in activities that may contribute to their human capital.

Two key patterns highlight this developmental potential. First, a relatively high proportion of respondents (61%) participated in some form of learning or self-development activity during maternity leave. Moreover, those who engaged in such activities often did so in multiple forms, suggesting not only openness but also sustained involvement in development. Second, voluntary work, although less widespread, was characterised by a relatively high time investment among participants. This indicates that for a subset of mothers, maternity leave includes regular and meaningful engagement in activities that may foster transferable skills.

From a human capital perspective [14], both learning activities and voluntary engagement can be interpreted as forms of skill and competency development. These activities may contribute not only to individual growth but also to the value that returning mothers can bring to organisations. In this sense, maternity leave can be seen as a period during which human capital is not necessarily depreciated but, in some cases, actively developed.

At the same time, the results suggest that participation in these activities is not evenly distributed across the sample. Learning attitudes appear to play a key role in shaping behaviour. The cluster analysis revealed that mothers who hold a more positive view of learning during maternity leave are more likely to engage in both training and voluntary work. In contrast, those who perceive childcare responsibilities as a barrier are less likely to participate in such activities. This finding underscores the importance of perception: the extent to which mothers perceive learning as feasible during this life stage may significantly influence their actual behaviour.

The strong association between learning activities and voluntary engagement further supports the interpretation that these behaviours are interconnected. Rather than isolated actions, they may reflect a broader development-oriented mindset. This aligns with previous literature suggesting that the outcomes of career interruptions depend on how individuals use this period [12], [13].

These findings have important implications for both families and organisations. As learning attitudes appear to influence engagement in development activities, external support and encouragement may play a key role in fostering such behaviour. Supporting mothers in recognising the possibility of effective learning during maternity leave—and providing accessible opportunities—may increase their motivation to engage in development-oriented activities. From an HR perspective, this suggests that organisations could benefit from acknowledging and building on these experiences upon return, rather than treating maternity leave solely as a period of absence. In this context, supportive organisational practices, particularly the role of supervisors and workplace culture, are essential for facilitating successful reintegration [19], [20]. Recognising and valuing

development activities undertaken during maternity leave may also help reduce maternity bias and promote more inclusive career trajectories.

However, the results should be interpreted with caution. The relatively small sample size limits generalisability, and the cross-sectional nature of the data precludes causal conclusions. The findings are therefore exploratory, but they point to meaningful patterns that warrant further investigation.

Conclusions

This study aimed to explore learning attitudes, self-development activities, and voluntary engagement during maternity leave among mothers who have recently returned to the labour market. The results provide preliminary evidence supporting the perspective that maternity leave can represent a period of active development.

The identification of two distinct attitudinal profiles highlights the importance of learning attitudes in shaping behaviour during maternity leave. Mothers with a more positive attitude towards learning are more likely to engage not only in training but also in voluntary work, suggesting a broader development-oriented mindset. These results provide preliminary evidence that different forms of activity during maternity leave are interconnected and may contribute to the accumulation of human capital.

From a theoretical perspective, the study reinforces the relevance of human capital theory in understanding maternity leave not as a gap but as a potential period of skill development and transformation. From a practical perspective, it points to an underutilised opportunity for both individuals and organisations. Recognising learning and voluntary activities as valuable forms of human capital may support more effective reintegration and help challenge prevailing assumptions about career interruptions.

Future research should build on these findings by using larger, more diverse samples and longitudinal designs to better understand the long-term impact of developmental activities during maternity leave. Furthermore, integrating qualitative insights—such as those planned in the broader research project—may provide a deeper understanding of the motivations, constraints, and perceived outcomes associated with these activities.

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Comparative analysis of the financial performance and profitability of Hungarian and Polish agricultural enterprises

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Abstract: The factors influencing the financial situation of agricultural enterprises in the new Member States have fundamentally changed since the EU enlargement in 2004. This research scientifically analyzes the main financial indicators on profitability in 2016-2023. The study is based on a significant amount of data on the financial situation of Hungarian and Polish agricultural enterprises. Descriptive statistical calculations and regression analysis were performed based on data from 1,000 Hungarian and 1,000 Polish enterprises collected from the Crefoport Company Information Database, covering eight years. The research further evaluates and synthesizes relevant domestic and international literature and statistics. The analysis of the data shows that the financial performance of the enterprises in the two countries differs. Based on the trends, it is established that the Hungarian agricultural enterprises underperformed the growth of indicators expressing the financial performance that of Polish agricultural enterprises during the examined period. In order to strengthen these enterprises, the research draws further conclusions and formulates recommendations.

Keywords: agriculture, profitability, ROE, ROA, ROS, profit margin

1 Introduction

The examination of profitability - in addition to the analysis of the financial and asset situation-, is important. Together they provide a more comprehensive picture of the financial situation of agricultural enterprises. In this research, we deal with the profitability in terms of Hungarian- and Polish cooperative agricultural

enterprises. The data for the analysis were provided by the Crefoport Company Information Database, which collects figures from publicly available and authoritative sources in a structured manner. According to their official information, the system collects data from nearly 1 million business companies, sole entrepreneurs, civil organizations and budgetary bodies in Hungary alone, and this is supplemented by some Visegrád 4 countries [3].

Analyses based on the Crefoport database form the basis of numerous studies, especially in the examination of corporate financial performance, competitiveness and regional economic processes. There are analyses that focus on a detailed examination of a particular sector, among others, Lendvai et al. analyzed the economic performance of Hungarian international automotive companies between 2008 and 2020 using the Crefoport database [16]. The main finding of the analysis is that the economic performance of the international automotive companies in Hungary are highly concentrated in space and plays a decisive role in domestic industrial growth, exports and employment, while their performance is sensitive to global economic crises and international market changes. In addition, Molnár et al. examined the profit persistence and market competition of Hungarian plastics companies, also based on the Crefoport database [19]. The authors' most important finding is that in the case of Hungarian plastics companies, profitability proved to be partly permanent, i.e. companies that achieved higher profits in the past were more likely to remain profitable later on. This suggests that market competition does not completely equalize the performance differences between companies in the short term. It is particularly important to identify the factors that contribute to the successful operation of businesses, so that we can later formulate related action proposals [17].

The analysis of the profitability of agricultural enterprises has also been the focus of several studies in recent years. Several authors have pointed out that the sector's profitability is significantly influenced not only by corporate efficiency, but also by farm size, capitalization, the support system, and regional characteristics. Fogarasi and Latruffe, examining the competitiveness and performance of Hungarian agricultural enterprises, concluded that larger, more efficiently operating farms typically have more favorable profitability indicators, while the profitability of smaller players is more vulnerable to market and cost shocks [10]. Economic shocks appeared differently in the profitability indicators of individual enterprises [11]. In addition, Bakucs and his co-authors emphasized that increasing productivity, technological developments, and the stabilizing role of subsidies are of paramount importance in the profitability of agricultural enterprises [1]. Based on research, it can be concluded that the long-term improvement of the profitability of agriculture can be achieved primarily by increasing efficiency, increasing added value and developing policies that support competitiveness [2].

2 Literature review

Hungarian and Polish agriculture have undergone significant structural transformations since 2004, in which accession to the European Union played a decisive role. The support system of the common agricultural policy, the integration of markets and technological modernization have all contributed to the agricultural enterprises of both countries operating in a new competitive environment. Although the economic weight of the sector has decreased, it has remained of strategic importance due to the maintenance of food self-determination, rural employment, export performance and territorial cohesion [5], [24].

When examining financial performance, the literature points out that Hungarian and Polish agricultural enterprises have different structural characteristics. In Hungary, larger-scale corporate enterprises and a more concentrated ownership structure are more typical, while in Poland a higher proportion of smaller family farms can be observed, which results in a specific cost and profitability structure. Polish agriculture has a stronger internal market base and a larger population background, while in the case of Hungarian agriculture, export orientation plays a more prominent role [4], [21].

According to analyses based on the European Commission's FADN database, the profitability of agricultural enterprises in the two countries showed an improving trend after 2004, but this was accompanied by significant fluctuations. Income developments were largely influenced by changes in crop prices, rising input costs, and weather extremes. The role of subsidies is prominent in both countries, and in the case of many farms they form the basis for the stability of operating results [7].

According to FADN data, the net income of Polish agricultural enterprises showed a more dynamic growth trajectory between 2013 and 2023 than that of Hungarian enterprises. While the development of income in Hungary was characterized by greater volatility, in Poland a more sustained and balanced expansion can be observed in the period under review. The difference between the two countries increased further by 2023, when the net income of Polish enterprises per farm approached EUR 44 thousand, compared to EUR 34 thousand in Hungary. This suggests that the Polish agricultural sector adapted more flexibly to the unfavorable macroeconomic environment.

Year	Hungary	Poland
2013	~17 000	~15 000
2016	~18 500	~21 000
2019	~26 000	~29 000
2021	~31 000	~38 000
2022	~39 000	~47 000
2023	~34 000	~44 000

Table 1

Farm Net Income (EUR/farm)

Source: Own editing based on the FSDN Public Database (2026)

The breakdown by farm size shows that in both countries the profitability of medium and larger farms was more favourable compared to smaller farms. At the same time, in Poland medium-sized family farms were also able to maintain a competitive income position, which may indicate more developed market integration and more efficient economies of scale. Overall, farm size can be considered a significant factor in both countries.

Size	Hungary	Poland
Small	Low	Medium
Medium sized	Mediums	High
Large	High	High

Table 2

Net income, 2023 (EUR/farm)

Source: Own editing based on the FSDN Public Database (2026)

The financial performance of Hungarian agricultural enterprises is typically supported by higher asset intensity, mechanization and production volume per larger area, while profitability is more exposed to changes in export market demand. In Poland, on the other hand, a more diversified economic structure and a greater role of family labor can mitigate the impact of cost shocks, while the smaller farm size can limit efficiency reserves [23], [22].

Examining the capital structure, it can be stated that Hungarian agricultural enterprises have a higher proportion of investments financed from loans, especially in the field of machinery and technology developments. In Poland, financing based on own resources and family capital is traditionally more prominent, although EU

resources and preferential loans have increased investment activity here as well. As a result of modernization, productivity improved in both countries, which also supported the increase in profitability indicators in the long term.

The literature also points out that in terms of future success, not only economies of scale, but also increasing added value, increasing the level of processing, digitalization and the spread of sustainable farming models will be decisive. Despite the differences between Hungarian and Polish agriculture, generational change, climate change and managing market volatility appear as common challenges [9].

Overall, it can be stated that the financial success of Hungarian agricultural enterprises is supported by a model based on larger farm size and export orientation, while in Polish agriculture, the broader entrepreneurial base and more flexible family economic structure represent a competitive advantage. In both countries, the support system continues to play a key role, but at the same time, increasing productivity and innovation form the basis for long-term competitiveness.

3 Methodology

The analysis is carried out in a comparative dimension, in which the performance of Hungarian enterprises was compared with the results of Polish agricultural enterprises. The Polish sample was selected because, among the V4 countries, the Crefoport Company Information Database provides the most comparable structured corporate data set with the Hungarian reporting system for Poland.

The research is based on primary and secondary data sources. The empirical study is based on the Crefoport Company Information Database, from which we extracted data from the financial reports of Hungarian and Polish agricultural companies. The use of the database was supplemented by the processing of additional relevant statistical and literature sources in order to address any data gaps, methodological changes and interpretation limitations of the period under review. During the secondary research, we used several scientific databases and search engines to establish the literature background, in particular the systems of MTMT, ResearchGate, Google Scholar and ScienceDirect.

The empirical study is based on a quantitative methodological approach. The sample included 1,000 Hungarian and 1,000 Polish agricultural cooperatives, based on data for the period 2016–2023. The sample size allows for the exploration of trends, correlations and structural features of the studied population.

The applied methodology includes descriptive statistics, correlation analysis and multivariate analysis procedures. As a first step, we performed a descriptive statistical analysis using Microsoft Excel software in order to present the basic

characteristics of the data, during which we determined, among other things, the average, median, minimum, maximum and standard deviation values.

Following the descriptive analysis, we used correlation calculations to explore the relationships between financial variables, and then we examined the impact of the factors determining profitability using regression models. The calculation of the indicators was done by variable, so in each case only valid data belonging to the given indicator were taken into account, as a result of which the number of valid and missing cases may differ by indicator.

The structure of the dataset also enables the future application of panel-data models. It makes it possible to control for unobservable firm-specific effects and temporal heterogeneity, thereby improving the robustness of the estimated relationships between profitability indicators and explanatory variables.

Profitability was measured alternatively by return on equity (ROE), return on assets (ROA), return on sales (ROS), and profit margin indicators. The combined use of these indicators allows for a complex assessment of return on equity, asset utilization, sales efficiency, and operating profit-generating ability.

Return on equity (ROE) expresses the income-generating ability of owner capital, which was calculated as the ratio of after-tax profit to owner capital:

$$\text{ROE} = \text{Revenue after taxation} \div \text{Equity}$$

A higher ROE value indicates more efficient capital utilization, but the distorting effects resulting from the capital structure and possibly low equity must be taken into account when interpreting it.

Return on assets (ROA) measures the income-generating efficiency of the company's total assets:

$$\text{ROA} = \text{Revenue after taxation} \div \text{Total assets}$$

The indicator indicates how effectively the company utilizes its available resources, regardless of the financing structure.

Return on sales (ROS) shows the profitability of sales activities, i.e. what proportion of sales revenue is realized as after-tax profit:

$$\text{ROS} = \text{Revenue after taxation} \div \text{Net sales revenue}$$

A higher ROS value may indicate more favorable cost management and more efficient pricing.

The **profit margin** is used to measure operating efficiency at the plant level, which is defined as the ratio of the result of operating activities to the net sales revenue:

$$\text{Profit margin} = \text{Results of the operation} \div \text{Net sales revenue}$$

This indicator primarily reflects the profit-generating ability of the company's core activity, and is therefore well suited for the comparative assessment of operating performance.

The panel approach allows the separation of time effects related to macroeconomic shocks – such as the COVID-19 pandemic, inflationary pressures and the 2022 drought – from firm-level operational characteristics. Although the present study primarily focuses on descriptive and comparative statistical analysis, the panel-data perspective provides an important methodological basis for future research.

The joint examination of the four indicators enabled the temporal and international comparison of the profitability position of Hungarian and Polish agricultural cooperatives.

As a result of the research, the similarities and differences observed in the profitability of Hungarian and Polish agricultural cooperatives can be revealed, and the financial and external environmental factors that played a decisive role in the development of corporate performance in the examined period can be identified. In future extensions of the research, fixed-effects and random-effects panel estimations could be applied in order to control for unobservable heterogeneity across enterprises and years.

4 Results

4.1 Return on Equity (ROE)

This indicator measures the company's profitability on its equity.

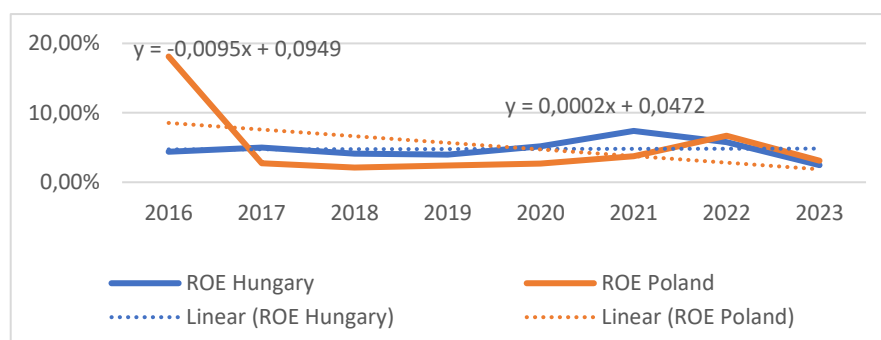


Figure 1

ROE-return on equity, 2016-2023

Source: Own editing, Crefoport Company Information Database (2025)

Based on the development of ROE, moderate owner return could be observed in agricultural enterprises in both countries between 2016 and 2023. In the Hungarian sample, the indicator fluctuated between 2.5–7.4%, with an average of 4.8%, with an essentially stagnant trend. In the case of Polish enterprises, after the outlier in 2016, ROE adjusted between 2.0–6.7%, with the period average being 5.2%.

Neither country consistently reached the band above 10%, which is considered favorable in international comparison, which suggests that the return on owner capital was limited by low operating margins, moderate asset turnover, and restrained financial leverage. According to the results of the ANOVA, no statistically significant difference can be detected between the average ROE values of the two countries ($F = 2.89$; $p = 0.1149$).

4.2 Return on assets (ROA): comparison of alternative measurement approaches

Return on assets (ROA) is one of the most important indicators of corporate performance, as it expresses the efficiency with which the company is able to utilize its available assets to generate profit. In this research, ROA was examined based on two methodologically different data sources: on the one hand, an approximate indicator created from the FADN database, and on the other hand, based on the classic accounting ROA calculated from the company reports of Crefoport. The parallel application of the two approaches made it possible to evaluate the performance of the agricultural sector from both a farm economics and a corporate financial perspective.

The FADN database does not publish a ROA indicator directly, therefore, using an approximate procedure accepted in the literature, we created a return on assets indicator from the ratio of Farm Net Income to Total Assets. Based on the results, Poland showed more favorable values every year between 2019 and 2023, the indicator ranged between 3.3 and 4.5%, while in Hungary it was between 2.5 and 3.8%. This indicates that at the level of average agricultural holdings, Polish farms realized higher income per unit of assets.

Year	Hungary	Poland
2019	2.8%	3.6%
2020	2.5%	3.3%
2021	3.1%	4.0%
2022	3.8%	4.5%
2023	3.0%	4.2%

Table 3

Approximate ROA (%)

Source: Own editing based on the FSDN Public Database (2026)

In contrast, in the case of agricultural partnerships included in the Crefoport database, the classic ROA indicator - based on the ratio of after-tax profit to total assets - showed a difference in favor of Hungarian businesses.

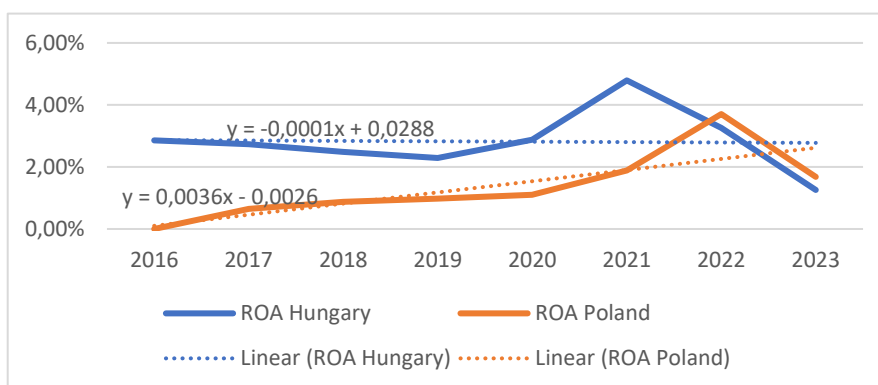


Figure 2

ROA-Return on Assets 2016-2023

Source: Own editing, Crefoport Company Information Database (2025)

During the period under review, the average ROA in the Hungarian sample was 2.8%, while in the Polish enterprises it was 1.4%. In Hungary, an improvement was observed especially in 2021–2022 (4.8% and 3.3%, respectively), while a decline occurred in 2023 (1.3%). In Poland, the indicator remained at a persistently low level between 2016–2021, increased to 3.7% in 2022, and then decreased again to 1.7% in 2023.

The difference between the two sets of results does not reflect a methodological inconsistency, but rather different structural dimensions of agricultural

performance. The FADN database contains a representative farm-level sample, in which individual and family farms are significantly represented, while the Crefoport analysis is based exclusively on companies operating in the form of partnerships. Consequently, the FADN results capture the farm efficiency of the agricultural sector as a whole, while the Crefoport data reflect the financial performance of a part of the sector.

Several structural factors can be assumed behind the difference. In Poland, the higher production flexibility, lower administrative cost level and stronger market integration of family farms may have resulted in more favorable farm-level returns. In Hungary, on the other hand, corporate enterprises are typically more capital-intensive, operate with greater economies of scale, and have a more advanced technological background, which may be reflected more favorably in the ROA indicator based on corporate reports [15].

Another explanatory factor may be the difference in asset valuation and accounting treatment. In agriculture, the valuation of land use, machinery, biological assets and inventories may differ by country and data source, which directly affects the denominator of ROA. In addition, the management of subsidies, the presentation of leased assets, and the tax environment can also modify the interpretation of the indicator.

Based on the results, it can be stated that Hungarian agricultural enterprises showed more favorable asset utilization in the corporate circle, while Poland performed better in terms of sectoral and farm-level efficiency. This indicates that the agricultural structure of the two countries follows a different development path: in Hungary, the more concentrated corporate model, and in Poland, the more competitive family economic structure, proved to be more effective.

From a methodological point of view, an important result of the dual approach is that ROA cannot be considered a universal indicator regardless of the data source. The interpretation of asset-based profitability is possible in each case by taking into account the specificities of the institutional environment, the company structure, and the database used. Therefore, the combined use of micro-level company data and representative farm-level data sources is justified for future comparative research.

4.3 Return on Sales (ROS)

Profitability relative to sales revenue shows how much profit the company is able to realize from sales.

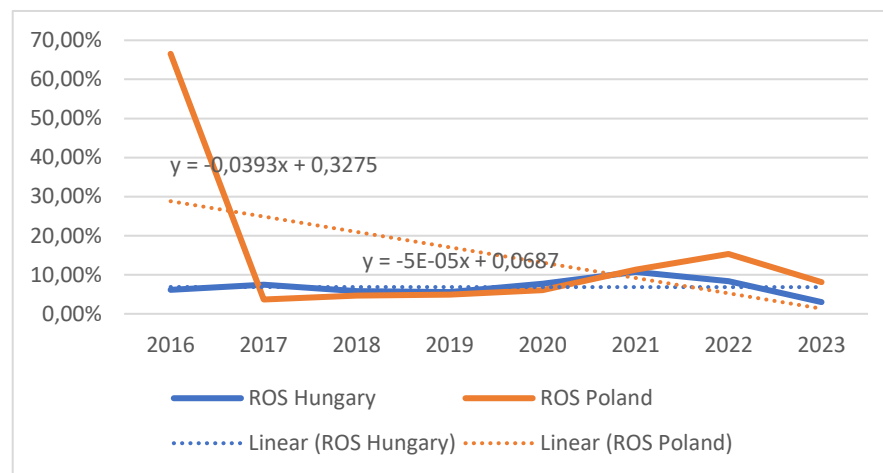


Figure 3

ROS-Return on Sales, 2016-2023

Source: Own editing, Crefoport Company Information Database (2025)

The profitability of Hungarian enterprises as a percentage of sales during the period under review was 6.9% on average, i.e. it was typically in the medium range associated with sustainable operations. At the same time, ROS decreased to 3.0% in 2023, which indicates a narrowing of the profit margin.

In the Polish sample, the median value of the indicator was 7.1%, but the time series showed significant fluctuations. After the extreme spike in 2016, a significant improvement was observed in 2021–2022 (11–15%), followed by a decline in 2023 (8.1%). The higher volatility of the Polish data suggests that profitability may have depended more strongly on market conditions, export demand or one-off profit effects.

4.4 Profit margin

The profit margin or profit ratio indicator reflects the company's operating efficiency and helps evaluate the profitability of the business model.

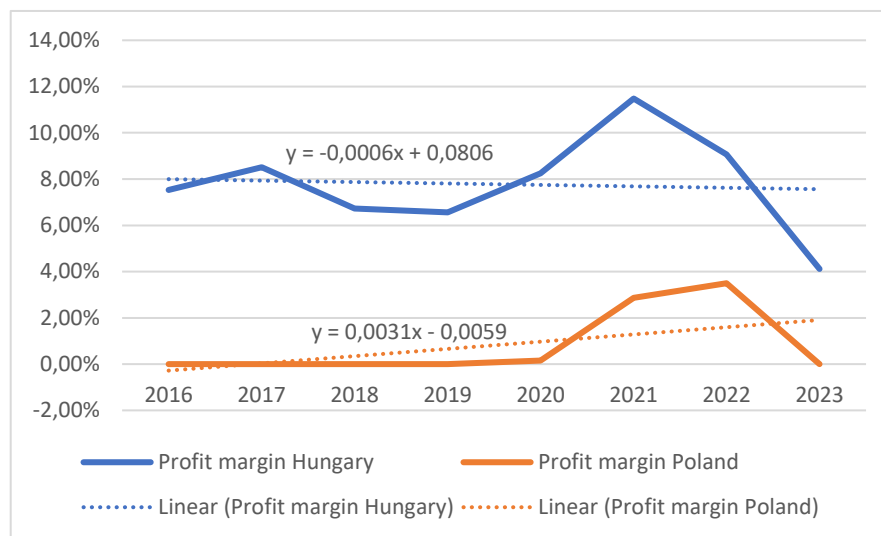


Figure 4

Profit margin, 2016-2023

Source: Own editing, Crefoport Company Information Database (2025)

Based on the profit margin, the operating efficiency of Hungarian agricultural enterprises showed a more favorable picture overall. The indicator was 7.8% on average and indicated a stable, positive operating margin in most years, although it decreased to 4.1% in 2023.

In the case of Polish enterprises, the profit ratio remained at a permanently lower level (0.8% on average), although an improvement was observed in 2021–2022. This suggests that although Polish enterprises realized higher net income, they worked with lower margins at the operating level, which may have been partially compensated by financial or support factors.

4.5 Relationship between profitability indicators

According to the correlation analysis, the relationship between profitability indicators in the Hungarian sample was closer than in the case of Polish enterprises. In Hungary, the ROE–ROA relationship showed a strong positive correlation ($r = 0.866$), while a near-perfect correlation was observed between ROS and profit ratio

($r = 0.985$). This suggests that corporate performance primarily depended on the development of operating efficiency and cost structure. In Poland, the relationships were more moderate (ROE–ROA: $r = 0.573$; ROS–profit ratio: $r = 0.821$), which indicates more heterogeneous business models, stronger market diversification and different corporate strategies. The profitability of Polish enterprises was presumably influenced to a greater extent by external factors, especially changes in export markets, the financing environment and the support system.

4.6 Synthesis of the results

Overall, the results show that between 2016 and 2023, Polish agribusinesses achieved more dynamic income growth, while Hungarian cooperatives operated with more favorable operating margins and a more stable internal profitability structure. The Polish model reflects greater growth potential, but also higher volatility, while the performance of Hungarian enterprises indicates a more moderate growth trajectory. Farm size, asset structure and operational efficiency proved to be determining factors in both countries.

5 Conclusions and recommendations

The aim of the research was to conduct a comparative analysis of the financial, asset and profitability situation of Hungarian and Polish agricultural enterprises in the period 2016–2023. During the evaluation, we interpreted the descriptive statistical, correlation and hypothesis testing results in an integrated manner, taking into account the effects of the COVID–19 pandemic, the Common Agricultural Policy (CAP) reforms and climatic shocks.

5.1 Main conclusions

Based on the results, the examined Hungarian enterprises showed a more favorable performance in terms of return on assets (ROA) and return on sales (ROS), which indicates more efficient asset utilization and stronger operating margins. In contrast, there was no clear Hungarian superiority in terms of return on equity (ROE) and profit ratio. This suggests that Hungarian corporate enterprises are more competitive at the operational level, but the efficiency of return on equity and capital structure remained limited.

The correlation between profitability indicators was stronger in the Hungarian sample, which indicates more homogeneous business models and greater internal consistency of corporate performance. In the case of Polish enterprises, weaker

correlations were observed, which indicates a more diversified operating structure, different financing models and stronger market differentiation.

However, the profitability indicators of Polish social agribusinesses showed greater volatility, with negative or extreme values in several years. This suggests that the growth potential may be higher, but corporate performance is more sensitive to market, regulatory and macroeconomic shocks. The performance of Hungarian enterprises, on the other hand, proved to be more balanced, but was accompanied by lower growth dynamics.

The decline of Hungarian ROA from 4.8% in 2021 to 1.3% in 2023 illustrates the sensitivity of export-oriented agricultural enterprises to macroeconomic and climatic shocks.

During the period under review, the COVID-19 pandemic resulted in significant adjustment pressures for agricultural enterprises in both countries. As a result of the uncertain market environment, enterprises adopted a more cautious borrowing behavior, increased their liquid reserves, and in several cases postponed their investments. This was particularly noticeable in Hungary, where the restraint in external financing was more pronounced.

The transitional period related to the new cycle of the CAP and the changes in support rules also influenced investment and financing decisions. The periodic narrowing of support sources restrained long-term developments, while new, sustainability-focused regulations caused cost increases in the short term. This was particularly evident in the development of profitability and liquidity indicators.

Among the climatic factors, the drought of 2022 should be highlighted, which significantly worsened production conditions in Hungary, reduced output and increased costs. As a result, investment activity deteriorated, the role of financial reserves increased, and the liquidity exposure of enterprises increased. In Poland, the production environment was more stable, which allowed for more favorable operational adaptation.

Macroeconomic developments also played a measurable role in the evolution of profitability indicators. Between 2021 and 2023, agricultural enterprises in both countries faced substantial increases in input costs, especially in energy, fertilizers and feed prices, partly driven by inflationary pressures and disruptions in international commodity markets. According to Eurostat data, agricultural input prices in the European Union increased sharply during 2022, with fertilizer and energy costs rising by more than 20% in several Central European countries, significantly reducing operating margins despite rising agricultural output prices [8].

The effects of these shocks appeared differently in the two countries. Hungarian enterprises experienced a sharper decline in profitability indicators after 2022, particularly in ROA and profit margin values, which may be associated with the severe drought conditions and stronger export exposure of Hungarian agriculture.

In contrast, Polish enterprises demonstrated relatively more stable income dynamics, supported by a larger domestic market and more diversified farm structures.

These findings suggest that macroeconomic resilience in agriculture depends not only on subsidy intensity, but also on the flexibility of production structures, financing conditions and market integration.

5.2 Policy and corporate governance proposals

Based on the results, it can be concluded that, under the current support and financing system, the long-term income-generating capacity of social agricultural enterprises is limited, especially without subsidies. Therefore, it is justified to design support systems in a more differentiated and targeted manner, which takes into account the different size, production structure and risk profile of individual company groups. Instead of sector-level, homogeneous regulation, it is more appropriate to apply a segment-specific approach.

In the case of Hungary, the primary objectives are:

- encouraging investments in technology and digitalization;
- improving cost efficiency and increasing the proportion of higher value-added products;
- strengthening liquidity reserves;
- expanding insurance and irrigation programs to manage climate risks.
- In the case of Poland, it may be justified to:
 - mitigating financing risks;
 - optimizing the debt structure;
 - improving the efficiency of inventory management;
 - Stabilizing highly volatile profitability through more conservative financial management.

A relevant goal for both countries is to strengthen the investment-incentive role of subsidies and to encourage the use of resources for productivity-enhancing and innovation purposes.

5.3 Scientific contribution and future research directions

The research contributes to the comparative assessment of the financial performance of Central European agribusinesses, especially in a period

characterized by a pandemic, regulatory transition, inflationary pressures and climate shocks. The results suggest that the resilience of the agricultural sector depends not only on the intensity of support, but also on firm efficiency, financing structure and adaptability.

From a methodological perspective, the research also highlights the applicability of panel-data approaches in comparative agricultural financial analysis. The integration of longitudinal enterprise-level data enables the future estimation of fixed-effects and random-effects models, which may provide more precise evidence on the causal relationships between profitability, subsidies and macroeconomic shocks.

The structure of the dataset also enables the future application of panel-data models, regional breakdown, and studies by firm size and sub-sector specialization. In addition, it would be useful to analyze in more depth the causal relationships between support, climate risks and financial performance.

Another promising research direction could be the application of the behavioral economics approach [13], especially the examination of the impact of behavioral and financial sunk costs [12]. Aspects related to the sustainability of production appeared among corporate operating goals as early as the 1970s, which are becoming an increasingly important issue with climate change [14]. In agriculture, the aspects of organic farming are also becoming increasingly decisive, which affect profitability [18].

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Has COVID-19 Transformed Crisis into Digital Acceleration? A Decade-Long Analysis of ERP Adoption across Countries

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Abstract: COVID-19 had a profound and far-reaching impact on digital transformation across various sectors and countries. However, it remains unclear whether it reduced structural differences in technology adoption or reinforced existing digital divides. This study examines ERP adoption dynamics across countries, including the effect of COVID-19. Using secondary data from the Eurostat database for the period 2015-2025, the study applies K-means clustering to examine cross-country differences in the share of enterprises adopting ERP systems for functional information exchange. Cluster analysis identified three statistically distinct groups: digital leaders, followers, and late adopters. Digital leaders maintain consistently high ERP adoption levels throughout the observed period. Digital followers start at a lower level than digital leaders but show the most dynamic growth. Late adopters display the lowest ERP adoption levels throughout the decade. Descriptive trends indicate a post-pandemic acceleration, suggesting COVID-19 as a potential catalyst for

intensified ERP adoption. Based on the study's outcomes, policy implications are suggested and future research directions are proposed.

Keywords: ERP systems, COVID-19, cluster analysis.

1 Introduction

Enterprise Resource Planning (ERP) systems are among the most important digital infrastructures in modern organisations, as they enable the integration of business processes and facilitate information sharing across functional areas [1]. At the macroeconomic level, these systems are also significant, as the diffusion of ERP systems reflects the broader digital maturity of national economies and their capacity to implement complex information systems.

The persistence of digital disparities across countries presents a significant scientific and policy challenge, particularly in the context of external shocks such as the COVID-19 pandemic. COVID-19 created uncertainty in the business environment and global economy, prompting companies to optimise their use of information technology [2]. During the crisis, organisations faced pressure from internal and external stakeholders, as well as concerns about their existence and survival, and had to focus on adopting emerging IT applications. The study [3] stated that, within a short period, employees had to perform their tasks without physical access to offices, while companies needed to accelerate digital transformation and rapidly implement new solutions.

Among the most widely adopted business software solutions were ERP systems, which are increasingly implemented across various industries as the backbone of companies. For example, SAP, a leading German software producer providing ERP system solutions, reported that demand for ERP systems is steadily growing and, in some markets, growth has exceeded expectations [4]. Similarly, [5] reported that ERP systems were among the largest categories of enterprise software spending, with an estimated annual growth rate of 7.1% from 2018 to 2022.

COVID-19 intensified the need for these systems within organisations, bringing about one of the biggest changes in the workplace: the limited presence of employees on company premises and the shift to teleworking [6].

While the pandemic accelerated digital transformation in many businesses and sectors, it remains unclear whether it reduced inter-country disparities by triggering a generalised digital response or whether pre-existing structural differences persisted or even intensified. In light of this research question, the present study examines the trajectory of ERP adoption across countries, including the impact of COVID-19.

Although previous studies consistently show that the COVID-19 pandemic accelerated ERP adoption, most findings are based on empirical evidence from single-country or single-company contexts. Existing research has largely used survey-based approaches conducted in specific national environments, which may limit the generalisability of the conclusions.

In this context, the use of advanced statistical methods offers a valuable complementary methodological approach. This enables systematic evaluation across diverse national contexts, which can strengthen existing empirical findings and provide a more comprehensive understanding of ERP adoption dynamics under COVID-19 conditions.

Extending the analysis beyond single-country empirical settings and applying statistical methods to a larger sample of countries may help to reinforce and generalise previous conclusions, while also offering a novel methodological perspective within ERP adoption trajectory research. By analysing the evolution of ERP adoption in 27 countries over a ten-year period and identifying structurally homogeneous groups of countries using K-means clustering, this study brings new cross-country insights.

The paper is organised as follows. The Theoretical Background provides a literature review on the topic. The Research Method section explains the methodological approach and statistical methods used. The main study outcomes are presented in the Results and Discussion section. The Conclusion highlights the study summary, implications, limitations, and future research agenda.

2 Theoretical Background

The measures introduced to mitigate the spread of COVID-19 led to increased use of technology and accelerated technological innovation. This helped to minimise harmful consequences for people's work activities, overall health, and wellbeing.

The transformation of business models into digital formats was widely adopted in response to dynamic environmental changes and has become more prevalent since the onset of the COVID-19 pandemic. One such trend was the growing adoption of ERP systems, driven by high demand for e-commerce. Furthermore, most institutions and organisations had to adapt their existing infrastructure by switching to digital tools to ensure smooth business processes. This enabled companies to survive during this challenging period [7]

Academics and researchers pay particular attention to the impact of COVID-19 on ERP system adoption. The study by [6] showed that cloud-ERP systems affected human resources' productivity during the COVID-19 era. Similarly, [3] used a survey to collect empirical data from small and medium enterprises in the Veneto

region of Italy before and after the outbreak of the COVID-19 crisis. The results showed that complexity and investment remain barriers to ERP system adoption, as do financial resources, employee training, and digital skills.

The study [8] tested the moderating role of COVID-19 on the relationship between digital accounting system use and system performance among manufacturing small and medium enterprises in Jordan. The main outcomes showed significant moderating effects, indicating that COVID-19 prompted the enterprises studied to upgrade their use of digital technologies. These findings highlight the importance of external environmental shocks in stimulating positive use of digital tools.

Research by [9] investigated the relationship between ERP applications and supply chain performance in steel re-rolling industries in Bangladesh during the COVID-19 pandemic. The findings support significant relationships among the variables studied, highlighting the role of easy and reliable data access and sharing, as well as improved efficiency and effectiveness.

The study by [10] examined the effects of the COVID-19 pandemic as a moderating variable on the adoption of cloud-based ERP systems. The study revealed a strong impact of COVID-19 on the Diffusion of Innovation theory and Technology-Organisation-Environment framework models, as well as on adoption intention, suggesting that COVID-19 has altered businesses' perceptions.

Based on referenced studies, the COVID-19 pandemic can be conceptualised as a significant external driver that accelerated digital transformation and reshaped organisations' technological priorities. The literature indicates that the pandemic increased the perceived necessity of integrated information systems, particularly ERP solutions, as firms were forced to ensure business continuity under conditions of remote work, disrupted supply chains, and heightened environmental uncertainty. These findings imply that the pandemic not only increased demand for ERP systems but also redefined them as critical enablers of organisational resilience and adaptability in turbulent environments.

3 Research Method

This study uses secondary data from the Eurostat database [11]. The selected indicator measures the percentage of enterprises that use an ERP software package to share information across functional areas within the organisation. The initial dataset included 36 European countries and covered six observation years within a ten-year period: 2015, 2017, 2019, 2021, 2023, and 2025. However, due to incomplete data for some years, countries with missing values for any year were excluded from the analysis. Specifically, Portugal, Sweden, Iceland, the United Kingdom, Bosnia and Herzegovina, Montenegro, North Macedonia, Albania, and Serbia were omitted to ensure methodological consistency. After data cleaning and

filtering, the final dataset comprised 27 countries with complete observations for all six years (Table 1).

Year → Country ↓	2015	2017	2019	2021	2023	2025
Belgium	74.11	77.51	75.21	78.45	79.87	84.38
Bulgaria	41.38	35.52	40.13	40.1	37.42	41.94
Czechia	57.99	53.07	68.05	63.74	55.12	76.38
Denmark	74.31	67.59	72.11	76.19	84.1	85.3
Germany	79.73	62.37	55.62	62.27	67.39	67.68
Estonia	39.70	41.43	42.91	42.65	57.08	64.04
Ireland	42.13	45.00	48.57	50.9	53.7	56.08
Greece	66.61	65.94	75.45	63.58	63.97	72.98
Spain	60.02	66.12	66.55	70.49	77.89	79.99
France	67.20	67.11	73.08	72.21	68.67	80.06
Croatia	48.14	46.75	47.43	45.59	47.78	51.8
Italy	61.79	64.77	60.68	59.56	65.2	71.88
Cyprus	74.51	60.76	60.61	56.19	63.67	59.8
Latvia	27.92	48.29	47.32	62.02	58.39	56.05
Lithuania	58.88	64.78	65.98	66.45	52.12	60.69
Luxembourg	58.06	60.27	61.48	60.23	66.14	69.33
Hungary	36.01	31.05	31.97	45.47	63.79	61.07
Malta	41.37	41.91	46.2	58.32	66.5	71.05
Netherlands	69.23	72.55	73.38	66.77	74.94	76.37
Austria	70.29	68.33	69.98	73.44	68.11	66.41
Poland	46.51	53.56	53.87	59.76	63.49	68.65
Romania	33.26	35.56	30.17	20.95	31.41	41.05
Slovenia	57.12	58.5	56.8	65.14	63.96	66.9
Slovakia	48.05	46.54	47.95	49.68	46.4	45.01
Finland	64.19	68.44	69.8	72.03	81.56	80.64
Norway	54.1	58.19	62.9	62.73	67.04	66.77
Türkiye	32.59	26.15	37.17	45.66	47.17	45.91

Table 1
Initial dataset

The initial dataset serves as the input for K-Means Cluster Analysis. This statistical method is widely used in research as a non-hierarchical clustering technique. The main objective of K-Means Cluster Analysis is to form clusters, or groups of countries, and to identify similarities within these clusters [12-13]. While hierarchical cluster analysis uses a single algorithm, K-Means Cluster Analysis employs a partitioning algorithm [14].

A key question in K-Means Cluster Analysis is how to determine the number of clusters [14]. In this study, K-Means clustering based on ERP implementation data was applied to identify three structurally stable groups of countries: digital leaders, digital followers, and late adopters. The number of clusters is determined primarily conceptually and in accordance with the research goal, rather than solely statistically. The aim is to group countries or entities into an interpretatively meaningful number of categories suitable for comparison and recommendations. Therefore, the number of clusters was set to three.

4 Results and Discussion

This research provides a data-driven perspective on the dynamics of ERP diffusion and contributes to the broader discussion of digital convergence and divergence within countries. Particular attention is paid to the COVID-19 period to assess whether it produced a homogenising effect or reinforced structural digital disparities.

K-means cluster analysis was used to identify structurally homogeneous groups of countries. The analysis classified countries according to similarities in their ERP digitalisation trajectories. Figure 1 presents the cluster memberships of the countries. Cluster 1 consists of Belgium, Denmark, Lithuania, Cyprus, Czechia, Germany, Finland, Slovenia, Norway, Spain, the Netherlands, Luxembourg, Austria, France, Italy, and Greece. Cluster 2 includes Hungary, Slovakia, Poland, Latvia, Malta, Croatia, Estonia, and Ireland. Cluster 3 comprises Romania, Türkiye, and Bulgaria.



Figure 1
Cluster memberships of the countries

Table 2 and Figure 2 present the final cluster centres, showing the average value for each year within each cluster.

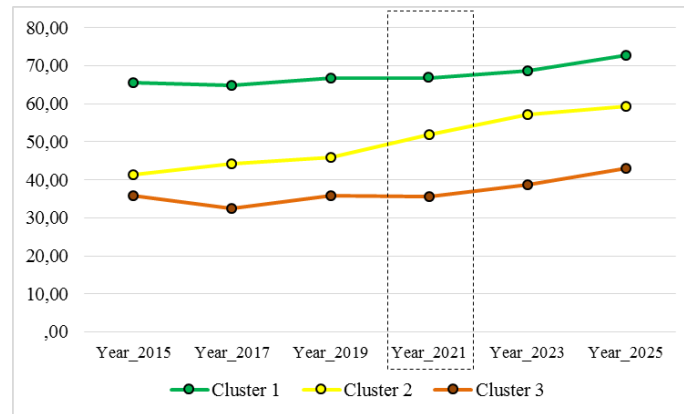


Figure 2
Graphical representation of final cluster centres

Cluster 1 comprises the countries with the highest levels of ERP implementation throughout the observed period, compared to Clusters 2 and 3. Therefore, these countries are Digital leaders. Cluster 2 includes countries with medium levels of ERP implementation and can be considered Digital followers. Cluster 3 consists of countries with the lowest levels of ERP implementation during the observed period, compared to the other two clusters. Therefore, these countries are Late adopters.

	Cluster 1	Cluster 2	Cluster 3
Y_2015	65.51	41.23	35.74
Y_2017	64.77	44.32	32.41
Y_2019	66.73	45.78	35.82
Y_2021	66.84	51.80	35.57
Y_2023	68.73	57.14	38.67
Y_2025	72.85	59.22	42.97

Table 2
Final cluster centers

According to [15], the COVID-19 pandemic began in March 2020 and ended in May 2023. Based on this, the present study considers 2021 as the year of COVID-19 impact within the examined ten-year period.

Digital leaders (Cluster 1) demonstrate consistently high ERP adoption levels throughout the observed period. Initial values in 2015 (65.51) already indicate a relatively mature stage of ERP diffusion. A steady upward trend is evident, culminating in the highest value in 2025 (72.85). The stability between 2015 and

2021 suggests structural digital maturity, while the more pronounced increase after 2021 may indicate accelerated digital transformation in the post-COVID period.

Digital followers (Cluster 2) start at a lower level in 2015 (41.23) compared to Cluster 1, but show the most dynamic growth pattern. The increase becomes especially marked after 2019, with a notable jump between 2019 (45.78) and 2021 (51.80). By 2025, the value reaches 59.22, indicating a convergence trend towards higher digital maturity. This suggests that countries in this cluster may also have experienced digital acceleration triggered by external shocks, such as the COVID-19 crisis, leading to intensified ERP implementation.

Cluster 3 exhibits the lowest ERP adoption levels throughout the period. Although a gradual upward trend is present from 35.74 (2015) to 42.97 (2025), the growth rate remains moderate compared to Cluster 2.

Table 3 presents the ANOVA test results. This test was applied to examine statistically significant differences among the clusters of countries.

	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
Y_2015	2198.29	2	52.303	24	42.03	0.000
Y_2017	1985.29	2	37.027	24	53.62	0.000
Y_2019	1933.73	2	39.857	24	48.52	0.000
Y_2021	1522.73	2	55.004	24	27.68	0.000
Y_2023	1273.89	2	71.616	24	17.79	0.000
Y_2025	1351.33	2	62.264	24	21.70	0.000

Table 3
ANOVA results

According to these results, there are statistically significant differences among clusters across all observed years (Sig = 0.000). Therefore, each observed year contributed significantly to cluster differentiation, confirming the robustness of the identified country typology.

Conclusion

This study examines the evolution of ERP adoption across European countries over a ten-year period, investigating whether distinct digital transformation trajectories can be identified at the cross-country level. Using K-means cluster analysis, countries were grouped according to the percentage of enterprises implementing ERP systems. The results reveal three relatively balanced and structurally differentiated clusters: digital leaders, digital followers, and late adopters. However, descriptive trends indicate a post-pandemic acceleration, suggesting COVID-19 as a potential catalyst for intensified ERP adoption. ANOVA results confirm statistically significant differences among clusters for all years, supporting the

robustness of the classification. From a policy perspective, the results highlight the need for differentiated digital transformation strategies, particularly for late adopters. Methodologically, the study contributes to the literature by demonstrating the applicability of clustering techniques in longitudinal cross-country analyses of technological adoption, offering an alternative to single-country or firm-level studies.

Despite its contributions, this study has some limitations. The first concerns the use of only one indicator, namely the percentage of enterprises implementing ERP systems, and the limited scope to expand the analysis to a broader international context beyond the observed countries, as the initial data set covers only European countries. Another shortcoming of the research is the failure to use formal cluster validation methods, such as the silhouette score, elbow method, or other measures of partition quality.

Future research could extend the analysis by incorporating additional macroeconomic and digital infrastructure indicators to further explain the observed cluster structure. Additionally, fuzzy cluster analysis could be applied to obtain results that may serve as a basis for comparison.

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Digital Transformation Strategies for Azerbaijani SMEs to Strengthen Integration into Global Value Chains

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Abstract: Azerbaijani small and medium-sized enterprises (SMEs) confront persistent hurdles in global value chain (GVC) integration, exacerbated by outdated digital infrastructure and reliance on traditional oil-dependent sectors. This study examines digital transformation strategies as a vital mechanism for enhancing SME competitiveness, particularly relevant amid Azerbaijan's economic diversification post-oil boom and the worldwide Industry 4.0 shift, where digital tools enable resilient supply chain participation. This study employs a quantitative benchmarking approach using bivariate correlation analysis (Pearson's r) to examine the link between digital adoption and the economic performance of Azerbaijani SMBs from 2018 to 2024. Utilizing official data from KOBİA and the State Statistical Committee, the analysis assesses how internet integration influences SMB value-added share within the non-oil sector.

The study proposes a multi-dimensional framework to integrate Azerbaijani SMEs into global value chains. Key strategies include establishing a National Digitalisation Strategy aligned with "Azerbaijan 2030," enhancing regional digital infrastructure, and expanding access to digital financing. Additionally, the paper emphasizes the need for targeted ICT skills training, standardized interoperable data platforms, and robust cybersecurity frameworks. Implementing these coordinated measures aims to bridge the digital divide, enhance productivity, and bolster the global competitiveness of the SME sector.

1 Introduction

Azerbaijan's economy, long anchored in oil exports, faces a pivotal transition toward diversification, yet small and medium-sized enterprises (SMEs)—which constitute over 90% of businesses and employ the majority of the workforce—struggle to integrate into global value chains (GVCs). Persistent challenges, including outdated digital infrastructure, limited access to international markets, and vulnerability to supply chain disruptions, hinder their competitiveness amid the global Industry 4.0 paradigm. Digital transformation emerges as a critical enabler, leveraging technologies like cloud computing, blockchain, and data analytics to enhance resilience, efficiency, and GVC participation. This is especially urgent post-oil boom, as Azerbaijan aligns with national strategies such as the 2030 Socio-Economic Development Program, which prioritizes digitalization for non-oil sector growth.

Despite growing literature on GVC integration in developing economies, few studies address SMEs in oil-dependent contexts like Azerbaijan, where digital adoption lags regional peers [20]. This paper bridges that gap by examining digital transformation strategies that empower Azerbaijani SMEs to embed sustainably in GVCs.

As Azerbaijan seeks to diversify its economy, the digital transformation of Small and Medium Enterprises (SMEs) has become a critical priority. This study evaluates the relationship between digital adoption and economic performance from 2018 to 2024, utilizing quantitative indicators to determine how internet usage correlates with SMB contributions to the non-oil sector. The findings inform a proposed multi-dimensional roadmap focused on infrastructure upgrades, financial accessibility, and data standardization. By aligning these strategies with national objectives, the research highlights a pathway for Azerbaijani SMEs to transition from local players to competitive participants in global value chains

2 Literature Review

The integration of small and medium-sized enterprises (SMEs) into global value chains (GVCs) has been widely examined within the domains of international business, development economics, and digital transformation. Existing literature consistently emphasizes that digitalization serves as a critical enabler for SMEs to overcome structural constraints such as limited scale, market access barriers, and inefficiencies in production and logistics [6].

2.1 Digital Transformation and SME Competitiveness

Digital transformation refers to the adoption of digital technologies—such as cloud computing, artificial intelligence (AI), blockchain, and enterprise resource planning (ERP) systems—to enhance business processes and value creation. According to [6], SMEs that adopt digital tools demonstrate higher productivity, improved innovation capacity, and stronger resilience to external shocks. Similarly, [13] highlights that digital adoption reduces transaction costs and enhances firms' ability to participate in cross-border trade.

The Industry 4.0 paradigm further reinforces this relationship. As noted by [12], technologies such as IoT and big data analytics allow SMEs to meet global standards, improve traceability, and integrate into digitally coordinated supply chains. However, the benefits are unevenly distributed due to disparities in digital readiness.

2.2 Global Value Chains and Digital Integration

The GVC literature suggests that participation depends not only on cost competitiveness but also on compliance with quality standards, transparency, and reliability [3]. Digital technologies play a pivotal role in meeting these requirements. For instance, blockchain-based traceability systems enhance trust and transparency in supply chains, which is particularly important in sectors such as agriculture and manufacturing [4].

Empirical studies show that SMEs utilizing digital platforms for internationalization can bypass traditional intermediaries, directly accessing global markets [1]. Furthermore, cloud-based ERP systems improve coordination across value chain actors, enabling real-time data sharing and operational efficiency [5].

2.3 Barriers to Digital Transformation in Emerging Economies

Despite its advantages, digital transformation among SMEs in emerging economies remains constrained. Key barriers include limited financial resources, inadequate digital infrastructure, low levels of digital literacy, and regulatory challenges [2]. The World Economic Forum [14] identifies a “digital divide” where SMEs in developing countries lag significantly behind their counterparts in developed economies.

In the context of resource-dependent economies like Azerbaijan, structural dependence on oil sectors further slows diversification and digital adoption. Studies

suggest that SMEs in such economies often lack incentives to innovate due to the dominance of extractive industries [15]. Additionally, insufficient access to financing for digital investments remains a critical constraint. 4. Role of Government Policies and Institutional Support

Government intervention is widely recognized as a key driver of SME digitalization. Policy instruments such as subsidies, tax incentives, digital training programs, and innovation hubs significantly influence adoption rates [6]. According to [16], coordinated public-private initiatives can accelerate SME participation in GVCs by improving infrastructure and fostering digital ecosystems.

Specific policy tools—such as SME digitalization grants, e-commerce facilitation programs, and GVC matchmaking platforms—have shown measurable impacts on export performance and firm productivity. For example, [17] reports that targeted digital capacity-building initiatives can increase SME export readiness by enhancing compliance with international standards.

2.4 Evidence from Azerbaijan and Comparable Economies

Academic literature on Azerbaijan remains relatively limited but growing. Existing studies indicate that while the country has made progress in ICT infrastructure, SME digital adoption is still at an early stage [18]. Government-led initiatives aimed at economic diversification and digital economy development have begun to address these gaps, particularly through e-government services and innovation support programs.

Comparative studies from similar post-Soviet and resource-rich economies suggest that digital transformation can significantly improve SME integration into GVCs when supported by institutional reforms and investment in human capital [19]. These findings align with broader empirical evidence that highlights the importance of digital skills and organizational readiness in maximizing the benefits of technology adoption.

2.5 Research Gap

While the global literature establishes a strong link between digital transformation and GVC participation, there is a lack of context-specific empirical research focusing on Azerbaijani SMEs. In particular, limited attention has been given to the effectiveness of recent government initiatives, the role of emerging technologies such as blockchain, and sector-specific digital strategies.

3 Digital-transformation strategies

Digital-transformation strategies that can help Azerbaijani SMEs integrate into global value chains:

- **Adopt a whole-of-government digital agenda** – create a National Digitalisation Strategy linked to the “Azerbaijan 2030 Vision” and a coordinating Digitalisation Commission to align ministries, set clear KPIs and monitor progress.
- **Upgrade digital infrastructure and ensure regional equity** – expand high-speed broadband, close the urban-rural gap, and provide shared connectivity hubs for SMEs in underserved areas.
- **Build digital skills and a culture of innovation** – launch targeted ICT training, partner with banks and tech firms to run academies, and embed digital-literacy modules in entrepreneurship programmes.
- **Facilitate access to finance for digital adoption** – offer preferential-rate loans and grants for software, hardware and e-commerce set-up, and develop credit-guarantee schemes that recognise intangible assets as collateral.
- **Standardise data and promote interoperable platforms** – develop common data standards, open-government APIs and a G-Cloud marketplace to allow SMEs to plug into national and cross-border digital services.
- **Strengthen cybersecurity and regulatory frameworks** – enact a National Cybersecurity Strategy with SME-specific safeguards, and simplify licensing for digital services.
- **Accelerate e-commerce and digital marketing adoption** – provide advisory support for website development, online sales channels and professional digital-marketing plans, leveraging the Asan portal and other e-gov tools.

Implementing these coordinated measures can close the digital gap, boost productivity and position Azerbaijani SMEs as competitive participants in global value chains (Figure 1).

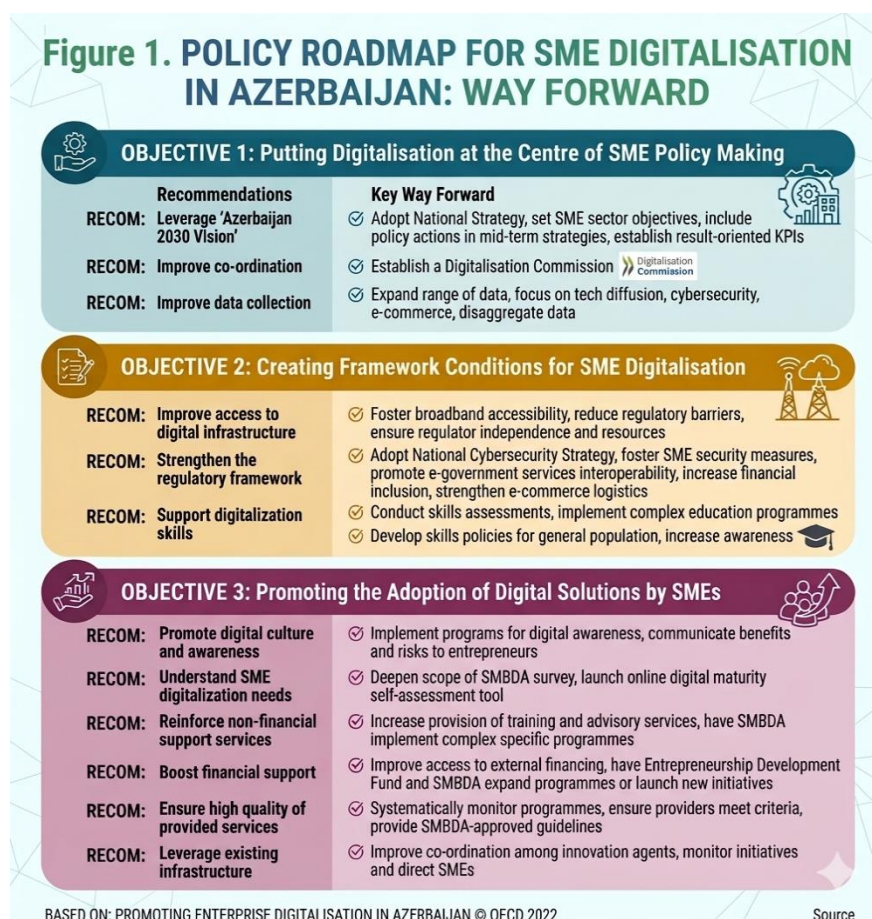


Figure 1.
Policy roadmap for SME digitalization in Azerbaijan: way forward

4 Methodological Approach

To complement the qualitative case studies, this research utilizes quantitative benchmarking. This process involves the analysis of secondary data to assess the digital and economic trajectory of Small and Medium Enterprises (SMEs) in Azerbaijan relative to global trends.

Data Sources and Instrumentation

The quantitative indicators for Azerbaijan were extracted from two primary official repositories:

- **Economic Performance Data:** Statistics regarding the "Share of SMBs in Non-Oil Sector Value Added" were sourced from the **Small and Medium Business Development Agency of the Republic of Azerbaijan (KOBİA)** annual reports and the **State Statistical Committee of the Republic of Azerbaijan**.
- **Digital Adoption Metrics:** Data on the "Share of Enterprises Using the Internet" was retrieved from the **Open Data Portal of Azerbaijan**, specifically the dataset on key indicators of ICT use in enterprises provided by the State Statistical Committee.

Statistical Analysis: Correlation of Digital Adoption and SMB Performance

To evaluate the relationship between the digital transformation of the economy and the economic contribution of Small and Medium Businesses (SMBs), a bivariate correlation analysis was performed. This analysis specifically examines the link between the **Share of Enterprises Using the Internet** (as a proxy for digital adoption) and the **Share of SMBs in Non-Oil Sector Value Added** over a seven-year period (2018–2024). Timeframe strictly determined by the availability of official data published by KOBİA and the State Statistical Committee of the Republic of Azerbaijan. While a longer time series would typically be preferred for longitudinal analysis, this specific 7-year window captures the comprehensive, official data footprint available for both internet adoption rates and non-oil SMB value-added metrics concurrently. Consequently, it represents the most exhaustive data scope currently viable for this empirical evaluation

Data Variables and Sources

The study utilized two primary metrics to determine the degree of association:

- **Independent Variable (\$X\$):** The percentage of enterprises utilizing internet services, representing the pace of digital integration within the business environment.
- **Dependent Variable (\$Y\$):** The percentage share of SMBs in the non-oil sector's value added, representing the economic health and output of smaller enterprises relative to the broader non-oil economy.

Calculation Method

The strength and direction of the relationship were measured using the Pearson correlation coefficient (r), calculated using the following formula:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

Where:

- x_i and y_i are the individual sample points for digital adoption and SMB share, respectively.
- $\bar{x}$ and $\bar{y}$ are the sample means.

Preliminary Findings for Methodology Validation

The analysis yielded a **correlation coefficient of 0.64**, indicating a **moderate-to-strong positive correlation**. This suggests that as digital adoption among enterprises increases, there is a general upward trend in the value-added contribution of SMBs, though the relationship is not perfectly linear.

Key Trends Observed:

- **Digital Growth:** Internet usage among enterprises showed a consistent upward trajectory, growing from **52.50% in 2020** to a significant peak of **62.60% in 2024**.
- **SMB Stability:** Following an initial growth spurt in 2021 (rising from 23.70% to 27.50%), the SMB value-added share remained relatively plateaued, fluctuating slightly between **27.20% and 27.40%** through 2024 (Table 1).

Year	Share of SMBs in Non-Oil Sector Value Added (%)	Share of Enterprises Using the Internet (%)
2018	23.50%	52.90%
2019	24.60%	51.50%
2020	23.70%	52.50%
2021	27.50%	54.20%
2022	27.20%	54.80%
2023	27.20%	56.00%
2024	27.40%	62.60%

Table 1
Correlation between digital adoption of enterprises and the value-added share of SMBs

The moderate-to-strong nature of the correlation ($r = 0.64$) suggests that while digital adoption is a contributing factor to SMB performance, other external economic variables likely influence the value-added share, necessitating further multivariate analysis in subsequent sections of this study (Figure 2).

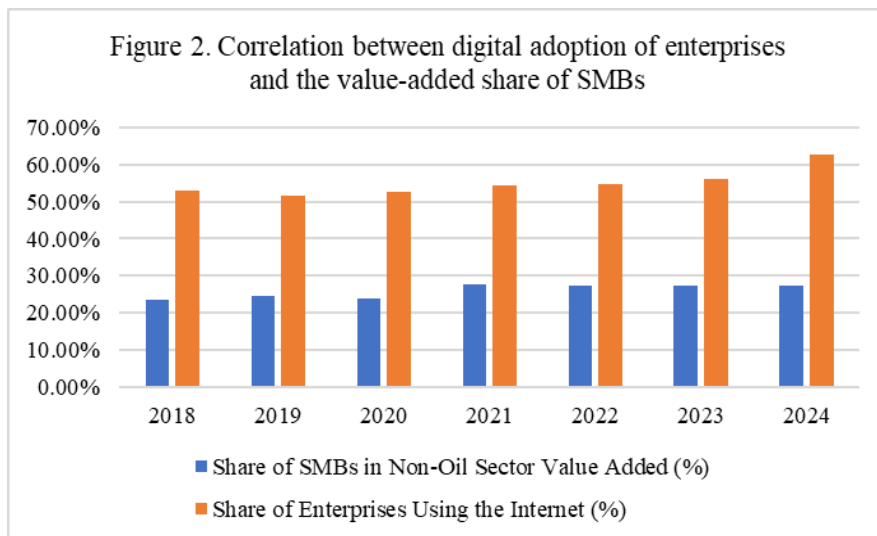


Figure 2
Correlation between digital adoption of enterprises and the value-added share of SMBs

Conclusion

The findings of this study underscore a pivotal moment for Azerbaijan's economic landscape. As the nation pivots away from its historical dependence on oil exports, the integration of Small and Medium Enterprises (SMEs) into Global Value Chains (GVCs) has transitioned from a strategic preference to an economic necessity. This research demonstrates that while digital transformation is currently underway, its full potential to catalyze SME growth remains partially untapped.

The quantitative analysis reveals a **moderate-to-strong positive correlation ($r = 0.64$)** between enterprise internet adoption and the value-added share of SMBs in the non-oil sector. While digital integration saw a significant surge—peaking at **62.60%** in 2024—the SMB contribution to the non-oil economy has remained relatively plateaued at approximately **27%** since 2021. This discrepancy suggests that "basic" connectivity (internet usage) is only the first step. For SMEs to truly break through local boundaries and compete globally, they must move beyond simple connectivity toward the adoption of sophisticated Industry 4.0 tools, such as blockchain for supply chain transparency and cloud-based ERP systems for operational efficiency.

The proposed **multi-dimensional framework** highlights that digital adoption cannot happen in a vacuum. To bridge the existing "digital divide," Azerbaijan must implement a coordinated approach that includes:

- **Infrastructure & Equity:** Closing the urban-rural gap to ensure regional SMEs have the same high-speed access as those in Baku.
- **Financial Innovation:** Developing credit-guarantee schemes that recognize intangible digital assets, thereby easing the capital constraints that currently hinder tech investments.
- **Human Capital:** Scaling ICT literacy and entrepreneurship programs to shift the business culture from traditional models to digital-first strategies.

In conclusion, the path to "Azerbaijan 2030" requires a robust digital ecosystem where SMEs are not merely observers of the digital economy but active, competitive participants in GVCs. By aligning national digitalization strategies with targeted institutional support and standardized data platforms, Azerbaijan can enhance the resilience of its non-oil sector. While the moderate-to strong correlation identified in this study confirms that digitalization is a vital engine for growth, it also serves as a call to action: technology alone is not a panacea. It must be paired with structural reforms and skills development to transform Azerbaijani SMEs from local players into global contenders.

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To examine the influence of CSR responsibility on consumer behavioral intention

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Abstract: This research examines the influence of Corporate Social Responsibility (CSR) perception on behavioral intentions of Safaricom PLC consumers. Using a sample size of 172 from Thika Town, Kiambu County, the study makes use of Exploratory Factor Analysis (EFA), Pearson correlation and simple linear regression to estimate the hypothesis that CSR perception significantly and positively affects consumer behavioral intention. The theoretical framework is grounded on [1], [2] and [3]. This outcome shows a strong positive correlation between CSR perception and behavioral intention ($r=.753$, $p<0.001$), with CSR perception identified to a strong predictor of behavioral intention. These findings show a significant implication for Safaricom's in terms of strategies, marketing, corporate communication, and the regulatory landscape of telecommunication in Kenya. In addition, the findings give insights to policymakers such as Communication Authority, to comprehend the dynamics of CSR as they model laws related to the telecommunications sector.

Keywords: Corporate Social Responsibility, Consumer Behaviour Intention and CSR perception

1 Introduction

1.1 Background of Study

The international business environment has widely embraced Corporate Social Responsibility (CSR) as a strategic tool. It is no longer viewed as a philanthropic duty; rather, CSR has morphed into a business framework that enables organizations to satisfy their ethical, legal, economic, and philanthropic obligations in society [1]. This transformation is especially noted in the telecommunications industry in Africa, where companies mingle with communities that have significant social needs and a higher consumer awareness. Safaricom PLC, a renowned telecommunications giant in Kenya, amplifies a successful integration of CSR

within the African corporate landscape. As reported in its 2022-2023 annual report [4], the organization noted that 1,250,581 people in the community benefited from health programs, 266,574 from educational sponsorships, and 241,220 from economic empowerment initiatives. However, despite this robust CSR framework, the true influence of these initiatives on consumer behavioral intentions such as choice, loyalty, and recommendation remains an empirical question that necessitates additional investigations. Scholars, including [1], [5], and [6] have convincingly demonstrated that CSR initiatives affect consumers' attitudes and behaviors. Nevertheless, there is insufficient empirical data that quantitatively evaluates the connection between CSR and behavioral intentions within the industry, specifically regarding Safaricom PLC. Therefore, this study seeks to address this gap by utilizing data collected from a sample size of 172 Safaricom customers in Thika Town, Kiambu County, Kenya.

1.2 Problem Statement

Although Safaricom PLC makes an impactful investment in CSR initiatives revolving around social, education, health, and economic sectors, the tangible impact of these efforts on consumers' behavioral intentions remains insufficiently documented in the current literature. In the absence of this empirical insight, Safaricom and comparable firms may accidentally misalign their CSR expenditures with consumer behavioral results, thereby constraining both their social influence and competitive edge.

The general objective of the study is to examine the influence of CSR responsibility on consumer behavioral intention among Safaricom PLC consumers.

1.3 Research question and hypothesis

In what ways does the Corporate Social Responsibility (CSR) perception affect the behavioral intentions of Safaricom consumers?

H1: Safaricom PLC's Corporate Social Responsibility perception has a significant positive influence on consumers' behavioral intention.

1.4 Scope of the Study

The research is confined to consumers of Safaricom PLC located in Thika Town, Kiambu County, Kenya. A total of 172 respondents participated in the survey. This study examines the link between CSR perception and behavioral intentions, using validated constructs based on Carroll's CSR pyramid.

2 Literature review

2.1 Corporate Social Responsibility

The contemporary understanding of Corporate Social Responsibility can be traced to [7], who initially raised the question regarding the obligations that business leaders have towards society. Over time, CSR has transformed from a charitable notion into a critical strategic business necessity. Carroll [1] explained this transformation with his four-dimensional pyramid, whereas [5] redefined CSR as a means of gaining a competitive advantage by fostering shared value, which revolves around a company's voluntary dedication to incorporating social and environmental issues into its business practices and interactions with stakeholders [8]. In Kenya, Safaricom PLC has synchronized its activities with its CSR initiatives with the Sustainable Development Goals (SDGs), investing in healthcare, education, environmental sustainability, and economic empowerment. Research consistently shows that transparent and effectively communicated CSR efforts are likely to elicit favorable responses from consumers [9]. [10] observed that Generation Z, shaped by digital connectivity and heightened awareness of social issues, demands greater transparency and ethical integrity from corporations, making CSR communication more critical than ever. [11] established that the fulfillment of commitments of sustainability promotes consumer loyalty and advocacy in a brand, particularly within the young demographic groups.

2.2 Carroll's CSR Pyramid

Carroll [1] suggests that the four-dimensional CSR pyramid behaves as the most critical theoretical framework for the application of CSR in this study. This pyramid delineates four interrelated responsibilities:

- **Economic Responsibility:** It is the duty to achieve profitability while offering quality products or services at fair prices.
- **Legal Responsibility:** It is the duty to function within legal parameters and adhere to regulatory standards.
- **Ethical Responsibility:** It is the duty to conduct oneself morally, honestly, fairly, and beyond legal obligations.
- **Philanthropic Responsibility:** It is a voluntary engagement in social initiatives such as healthcare, education, and environmental conservation.

Carroll [12] suggested that organizations that incorporate all four dimensions of the CSR Pyramid are more effectively positioned to cultivate stakeholder trust and attain a sustainable competitive advantage. This research introduced a fifth dimension, transparency, which increases the significance of transparent and sincere CSR communication in fostering consumer trust [6].

2.3 Consumer Behavioral Intention

Behavioral intention the extent to which a consumer is inclined to engage in a particular behavior [13]. Within the framework of Corporate Social Responsibility (CSR), behavioral intention manifests through three dimensions: Choices, Loyalty commitments, and the readiness to endorse a brand [14]. Therefore, the study opted to use the

- Choice: it is the act of choosing a company's offerings over those of its rivals, influenced by its corporate social responsibility.
- Commitments: It is the persistent dedication to utilizing a company's services over time.
- Recommendation: It is the readiness to endorse and suggest a company to others, grounded in its reputation for corporate social responsibility.

Kim and Lee [15] illustrated that ethical and philanthropic corporate social responsibility (CSR) initiatives enable corporate reputation and consumer assessment, which in turn affects purchasing intentions and customer Loyalty. These results hold significant importance in the Kenyan telecommunications sector, where customer decisions are shaped not only by the quality of the service and pricing but also by the perceived corporate citizenship.

2.4 CSR and Behavior Intention

The connection between Corporate Social Responsibility (CSR) and consumer behavioral intention has been examined across various industries. [16] carried out in the banking field and demonstrated that CSR significantly contributes to elevating the satisfaction of the consumers, loyalty, and positive word-of-mouth. In an equivalent way, [17] demonstrated that CSR activities can allow brands to have a competitive advantage in a crowded market by positively influencing consumer behavioral intentions. In the context of Africa, empirical research that evaluates this relationship is scarce. Most studies mainly focus on the developed economies [15]; [6], therefore creating a gap that this study aims to fill. The complete CSR activities of Safaricom PLC sectors, such as healthcare, education, and economic empowerment, give a crucial framework for analyzing this relationship within a developing economy. [18] demonstrated that companies whose CSR activities visibly address community needs attain higher levels of loyalty from consumers as compared to those whose efforts in CSR are vague. The clarity and authenticity of communication in CSR were identified as critical moderators of the relationship between CSR behavioral intentions, a finding that matches with the component of transparency integrated into the measurement of the CSR tool used in this study.

2.5 Theoretical Framework

This study is anchored on three entrenched theoretical frameworks:

1. **CSR pyramid** [1]: This model gives a five-dimensional framework and offers a five-dimensional application of CSR perception used in this research, encompassing the legal, ethical, philanthropic, and transparency dimensions.
2. **Expectation-confirmation Theory** [2]: This theory illustrates the process by which CSR activities affect behavioral intentions. When Safaricom PLC matches consumers' expectations, it gives satisfaction, which thereafter promotes behavioral intentions such as choice, loyalty, and recommendation.
3. **Stakeholder Theory** [3]: This theory stresses the significance of Corporate Social Responsibility by proposing that the functioning of business is influenced by stakeholders and their expectations influence the decisions made.

2.6 Conceptual Framework

The conceptual framework (Fig. 1) identifies the independent variable as CSR perception, while the dependent variable is identified as behavioral intentions.

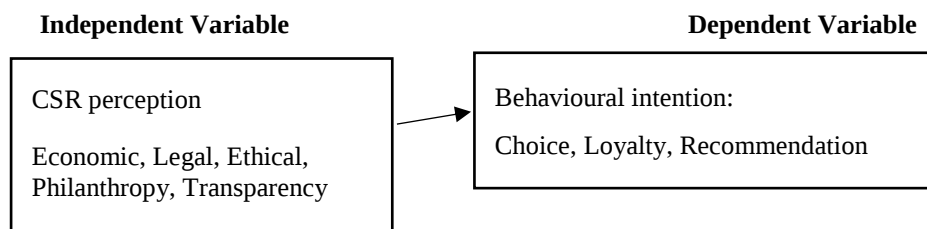


Figure 1
Conceptual Framework

3 Materials and Methods

3.1 Sample Size Determination

The sample size was calculated using the standard formula for proportion, which is particularly suitable when the targeted population cannot be defined precisely or is

large [19]. This method is commonly used in the field of social science studies where the size of the total population remains unknown. As noted by [19], getting an appropriate sample size requires the identification of three essential criteria: the level of precision, the level of confidence, and the extent of variability in the attributes being evaluated. In terms of variability, [19] explains that a proportion $p = .5$ signifies the highest level of lack of consistency within a population, and therefore it is frequently deployed to ascertain a more conservative sample size, which means that the sample size may exceed what would be calculated if the actual variability of the population attribute were applied. Given that the true population proportion of Safaricom subscribers in Thika Town was not known, $p = .5$ was used in this study to guarantee the most conservative and dependable estimate.

The formula (1 for proportions, as outlined by [19] (referencing Cochran) was used:

$$n = (Z^2 \times p \times q) / e^2 \dots\dots\dots(1)$$

Where:

- n = the necessary sample size
- Z = the Z-score that aligns with the cohesion confidence level
- p = the estimated proportion of the attribute present in the population
- $q = 1 - p$
- e = the desired margin of error (level of precision)

The study deployed a 95% confidence level, which suggests that 95 out of 100 samples will have a true population value within the defined precision range, corresponding to a Z-score of 1.96. Given that the actual population proportion was not known, p was set to .5, resulting in $q = 1 - .5 = .5$. The margin of error was established at .075.

$$n = \frac{(1.96)^2 * 0.5(1 - 0.5)}{0.075^2}$$

$$n = \frac{3.8416 * 0.25}{0.005625} = 170.74$$

The obtained value was later rounded up to 171 respondents. This outcome is further justified by Table 2 of [19], which outlines the recommended sample sizes at a 95% confidence interval with $p = .5$. For a population size of 300 and a precision level of $\pm 5\%$, Table 2 recommends a sample size of 172, which closely aligns with and supports the calculated value of 171 in this study. However, to ensure the reliability of the results and to account for incomplete non-responses or questionnaires, the final sample size was marginally increased to 172 respondents. [19] suggests that the sample sizes are often increased in size to balance non-response, and that the quantity of surveys distributed should exceed the minimum

necessary to achieve the desired level of confidence and precision. Therefore, a sample size of 172 was deemed fit to produce statistically valid results at 95% confidence interval.

4 Results

4.1 Sample profile

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	81	47.1%
	Female	91	52.9%
Age group	18-28	106	61.6%
	29-38	53	30.8%
	39-48	8	4.7%
	49-58	5	2.9%
Education	High School	29	16.9%
	Diploma	49	28.5%
	Undergraduate	64	37.2%
	Masters	25	14.5%
	PhD	5	2.9%
Safaricom subscriber	Yes	171	99.4
	No	1	0.6%
Duration	Under 12 months	13	7.6%
	13-60 months	31	18.0%
	Over 60 months	128	74.4%

Table 1
Demographic Profile of Respondents (n=172)

In table 1, Females comprised 52.9% of the sample. Young adults aged 18-28 represented a significant 61.6%. The distribution accurately mirrors a genuine

characteristic of Safaricom's subscriber base. A substantial proportion of the respondents were well-educated: 37.2% attained undergraduate degrees, 28.55 held diplomas, and 14.5% had attained their master's. This indicated that the sample is well educated and hence made an informed evaluation. Notably, 99.4% of the respondents confirmed their status as active Safaricom subscribers, with 74.4% having been customers for a duration of more than 60 months.

Descriptive Statistics of Survey Response on CSR Dimension

CSR Dimension	Strongly Agree %	Agree %	Neutral %	Disagree %	Strongly Disagree %
Economic Responsibility	26	39	20	9	6
Legal Responsibility	33	40	17	5	6
Ethical Responsibility	31	47	16	1	1
Philanthropic Responsibility	53	28	17	1	2
Transparency	34	34	18	9	4

Table 1
Shows the summary of the CSR response.

Table 2 shows that the aspect of philanthropic responsibility has the highest consensus rate of 81%, with 53% of the participants strongly agreeing, confirming that Safaricom embraces healthcare, education, and environmental sustainability.

Descriptive statistics of Survey of Behavioral Intention responses

Item	Strongly Agree %	Agree %	Neutral %	Disagree %	Strongly Disagree %
Choice	41	36	18	3	2
Loyalty	44	42	11	1	2
Recommendation	44	39	15	1	2

Table 3
Shows the summary of the behavioral intention response.

In table 3, Loyalty achieved the highest response rate with 86%, with 44% of the respondents strongly confirming that they will continue using Safaricom as their telecommunication company.

4.2 Exploratory Factor Analysis of CSR

Table 4 presents the Total Variance Explained for the CSR perception components. The analysis showed a single factor with an eigenvalue of 3.11, which represents 62.2% of the total variance. Using Kaiser theory, the four factors had eigenvalues that were below 1.0, and hence, they were not extracted [20]. The rotation sums of squared loadings confirm a similar figure of 62.2%, which makes rotation unnecessary. Therefore, it suggests all five items of CSR perception converge on a singular.

Total Variance Explained									
	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.11	62.2%	62.2%	3.11	62.2%	62.2%	3.11	62.2%	62.2%
2	.75	14.9%	77.2%						
3	.40	8.1%	85.3%						
4	.38	7.7%	92.9%						
5	.35	7.1%	100.0%						

Table 4
Eigenvalues (EV) and Total Variance Explained

EFA of Behavioral Intention

Table 5 shows the overall variance and the behavioral intention items. The analysis disclosed a single factor with an initial eigenvalue of 2.44, which represented a total variance of 81.4%. Factors with eigenvalues below 1.0 were not extracted.

Total Variance Explained									
	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.44	81.4%	81.4%	2.44	81.4%	81.4%	2.44	81.4%	81.4%
2	.43	14.3%	95.7%						
3	.13	4.3%	100.0%						

Table 5
Eigenvalues (EV) and Total Variance Explained

Kaiser's criterion [20] was used to validate the factors that were to be retained. Both constructs showed a strong unidimensionality.

Component Matrix of CSR

After rotation, the factor loadings remained the same in table 6, ranging from .62 to .85.

Rotated Component Matrix

	Component
	1
Safaricom_offer	.83
Safaricom_is_a	.79
Safaricom_pract	.85
Safaricom_spor	.62
I_think_that_sa	.83

Table 6
Results of Rotated Component Matrix of CSR

Component Matrix of Behavioral Intention

Table 7 established that choice had the lowest factor loading of .84, loyalty had a factor loading of .92, and recommendation had the highest factor loading of .95.

Component Matrix

	Component
	1
Due_to_the_CS	.84
I_will_continue	.92
I_would_sugge	.95

Table 7
Results of Rotated Component Matrix of Behavioral Intention

4.3 Reliability analysis

Reliability Statistics

Cronbach's Alpha	N of Items
.84	5

Table 8
shows the results of the reliability test on CSR perception.

Reliability Statistics

Cronbach's Alpha	N of Items
.88	3

Table 9

Reliability test on Behavior intentions

The evaluation of internal consistency was conducted utilizing Cronbach's Alpha. The perception of CSR, table 8, gave an $\alpha=.84$ across the five items, which signified a strong consistency. The behavioral intention, table 9, yielded an $\alpha=.88$ across the three items, which reflects strong reliability. Both coefficients produced a value that signifies that consistency was good [21]. Table 2 of [21] confirmed that the measurement tools used were reliable.

4.4 Correlation Analysis

The Pearson correlation analysis in table 10 showed a positive correlation between the CSR perception and behavioral intention ($r=.753$, $p<.001$). These results suggest that Safaricom customers who possess a more positive view of the company's CSR activities are equally inclined to show favorable behavioral intentions such as showing loyalty, choosing, and recommending the services of Safaricom to others. [22], argues that emotional attachment driven by CSR fosters consumer loyalty, and in the banking sector, [23] demonstrated that CSR initiatives produce significant positive effects for their organizations by improving the satisfaction of the customer and enhancing consumer behavioral responses.

correlation of CSR and Consmer behaviour intention			
	Column 1	Column 2	Column 3
CSR	1		
Column 2	0.719994	1	
Consumer Behaviour Intention	0.752742	0.701524	1

Table 10

Shows a correlation analysis.

4.5 Regression Analysis

SUMMARY OUTPUT(Regression on CSR & Behaviour Intention)								
Regression Statistics								
Multiple R	0.752742							
R Square	0.566621							
Adjusted R	0.564072							
Standard E	0.522309							
Observations	172							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	60.63578	60.63578	222.2665	1.1E-32			
Residual	170	46.37714	0.272807					
Total	171	107.0129						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	1.79845	0.039826	45.15803	1.35E-96	1.719833	1.877066	1.719833	1.877066
X Variable	0.629642	0.042233	14.9086	1.1E-32	0.546273	0.713012	0.546273	0.713012

Table 11

Shows the summary of the regression.

The regression model in table 11 gave results that were statistically significant, $F(1,170) = 222.27, p < .001$, suggesting that the perception of Corporate Social Responsibility serves as a strong and dependable predictor of consumer behavioral intentions. Perception accounted for 56.7 % of the variance in consumer behavioral intention ($R^2 = .567$, Adjusted $R^2 = .564$). This shows that CSR serves as a significant predictor of the behavioral intentions of Safaricom customers towards the brand. The remaining 43.3% of the variance can be contributed by other factors.

The regression coefficient for CSR perception was statistically significant ($B = .630$, $t = 14.91$, $p < .001$), affirming that CSR perception is a strong predictor of consumer behavioral intention. A unit increase in CSR perception, consumer behavioral intention increased by 0.630 units. Thus, the regression equation (2) is formulated as:

$$\text{Behavioral Score} = 1.798 + 0.630 (\text{CSR}) \dots\dots\dots (2)$$

These findings provide strong empirical evidence supporting the hypothesis that CSR perception positively and significantly influences consumer behavioral intention.

4.6 ANOVA-Demographic effect

One-Way ANOVA — Effect of Demographic Variables on Consumer Behavioural Intention								
Dependent Variable: Consumer Behavioural Intention (BhaveScore)								
Demographic Variable	Category	N	Mean	SD	F	df	p	Sig.
Gender	Male	81	1.893	0.752	2.203	-1,170	0.140	ns
	Female	91	1.714	0.819				
Age Group	18-28 years	106	1.764	0.856	0.527	-3,168	0.664	ns
	29-38 years	53	1.818	0.712				
	39-48 years	8	2.125	0.562				
	49+ years	5	1.800	0.380				
Education Level	Primary	29	1.437	0.557	2.043	-4,167	0.091	ns
	Secondary	49	1.918	0.983				
	Diploma	66	1.838	0.733				
	Degree	23	1.913	0.691				
	Postgraduate	5	1.667	0.624				
Length of Customer Relationship	Less than 1 year	13	1.333	0.527	2.666	-2,169	0.072	ns
	1-3 years	31	1.914	0.911				
	More than 3 years	128	1.818	0.771				
Note: $p < .001$ ns = not significant								
Customer variable excluded — all respondents are Safaricom customers (no group variation).								

Table 12
Demographic Variables on Consumer Behavior

Table 12 shows the one-way ANOVA results of demographic variables of consumer behavior intention. All p-values surpassed the .05 significance threshold, suggesting that they did not have an influence on CSR consumer behavioral intentions.

Conclusion and Recommendation

CSR and Consumer Behavioral Intention

The study indicates that the CSR perception significantly influences consumer behavioral intentions among Safaricom customers, with a strong positive correlation 8 ($r=.753$, $p<.001$). The CSR perception of CSR accounted for 56.7% of the variance in behavioral intention ($R^2=.567$, $F(1,170) = 222.227$, $p<.001$). This affirms that customers who hold the view that Safaricom is socially responsible are more inclined to show loyalty, continue using its services, and recommend it to other people. These results are consistent with stakeholder theory [3]. Therefore, CSR should not be held as a philanthropic duty; it should be used as a strategic tool to promote consumer loyalty and retention within the competitive telecommunications sector in Kenya.

Recommendations

For Safaricom Management

Safaricom should make strategic investments in a great way across all the CSR levels of Carroll's pyramid. The organization should enable its visibility on its CSR programs through traditional and digital media campaigns, which will assure the customers of its commitment to social responsibility.

For policy Makers

The Communications Authority of Kenya should establish a policy that encourages CSR investment among telecommunications firms by offering tax incentives, requiring CSR reporting, and implementing recognition programs for exemplary performance in social responsibility.

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Integrating artificial intelligence into agriculture in the EU

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Abstract: Artificial intelligence (AI) helps agriculture by automating routine tasks, optimizing decision-making, and making farming more efficient. Robots can perform physical work, drones can monitor crops and drought damage, and AI-based systems can assist with data analysis and farming decisions. Integrating artificial intelligence increases efficiency and reduces costs, but the digital transition and technology adoption also present challenges. Artificial intelligence is already embedded in many everyday devices used by businesses and consumers, often unnoticed. In recent years, the use of generative AI (GenAI) has spread rapidly across all sectors. For Europe, integrating artificial intelligence into agriculture is essential for competitiveness, while also enabling innovative solutions to be brought to market. This study analyzes the opportunities, barriers, and regulatory implications of AI adoption in European Union (EU) agriculture based on a qualitative assessment of a multi-stakeholder expert workshop organized by the European Commission. Using thematic content analysis, the research identifies key AI application domains, economic and environmental impacts, governance challenges, and adoption constraints—particularly for small and medium-sized farms. The findings indicate that although AI technologies such as robotics, decision support systems, and autonomous machinery demonstrate measurable potential in reducing inputs and improving efficiency, structural barriers including fragmented data ecosystems, regulatory uncertainty under the AI Act,

limited digital skills, and trust deficits significantly slow adoption. The study concludes that coordinated data governance, sector-specific liability clarification, targeted capacity building, and scalable business models are essential to unlocking AI's full competitiveness-enhancing potential in EU agriculture.

Keywords: artificial intelligence, smart agriculture, precision farming, EU AI Act, agricultural competitiveness, digital transformation, robotics, data governance

1 Introduction

1.1 The impact of artificial intelligence on competitiveness

Artificial intelligence (AI) is already an integral part of many applications in the everyday activities of businesses and consumers, although this is not always obvious at first glance.

Artificial intelligence is a complex algorithm that mimics human intelligent thinking, cognitive processes, and behavior, and is also capable of learning. It follows that AI can best develop where extensive and complex data sets are available [1]. Artificial intelligence is a tool that can enable smart agriculture to achieve goals that go beyond the limits of human capabilities. With its help, one of the challenges of the future will be to process huge amounts of data and transform it into actionable elements [2]. In agriculture, the use of artificial intelligence is not yet a mature practice for solving many of the tasks that arise. In production, in addition to controllable conditions, circumstances may arise over which farmers have no control (weather factors). At the same time, artificial intelligence helps to increase efficiency and reduce costs, leading to greater profitability [3].

There are many small businesses in agriculture, and after a while, these businesses are likely to become users of artificial intelligence applications. Although many farms already generate a lot of data, including from precision farming, the data from a single farm is unlikely to be sufficient for the effective and efficient development of AI models. Therefore, data sharing will be essential to exploit the potential of AI [4].

1.2 Digitization and precision farming as precursors to artificial intelligence

According to [5], precision farming refers to the practical application of digitized agriculture, the use of digital solutions in agriculture, where developments are aimed at more competitive farming and increased efficiency, while also placing

great emphasis on environmental sustainability. The dissemination of digitalization technologies and their widespread application in agricultural production is listed as the tenth objective of the Common Agricultural Policy after 2020, under the heading "Knowledge transfer, innovation, and digitalization."

According to [6], the widespread dissemination and application of digitalisation in agriculture could provide a solution for the development of sales channels for agricultural products in Hungary, enabling the opening of new sales channels. All these opportunities have already been outlined in Hungary's Digital Agricultural Strategy. Csiba & Ferencz [7] believe that, in addition to opening up sales channels, the above-mentioned strategic plan also recommends the use of higher-level digital precision technologies that promote the processing of products at a higher level and their development into products with higher added value. In addition, it emphasizes the need to make communication and, thus, business relations more efficient, which is also made possible by the widespread dissemination and application of digitalization.

As a result of this development, various digital tools and software are now available to farmers in Hungary. Farms are open to precision solutions, but there are also challenges to their successful dissemination, such as a suitably trained workforce, capital, etc. Precision farming is the practical manifestation of digitized agriculture, involving the application of digital solutions in agriculture, where developments are aimed at how to farm competitively and increase productivity, while placing great emphasis on environmental sustainability [8].

1.3 The impact of artificial intelligence on labor shortages

Artificial intelligence can be a significant help in solving labor shortages in certain areas of agriculture. In many farms, labor shortages and quality are serious problems. Artificial intelligence can help by automating many tasks, especially those that require significant human intervention. Good examples of this are self-driving tractors based on artificial intelligence and robots used in agriculture and other areas [9]. AI technologies are primarily used in large-scale farming to help solve problems caused by labor shortages, for example through the use of robotics. The use of self-driving robotic machines reduces operating costs and further improves crop yields [10]. According to farmers using AI, automated production can transform agriculture from labor-intensive manual work into intelligent, efficient activities powered by robotics and artificial intelligence. These technologies increase productivity and profitability on farms of all sizes [11].

The use of artificial intelligence also results in excellent efficiency and accuracy. GPS-controlled equipment and robotic machines operate with human-impossible precision, minimizing errors, reducing waste, and enabling real-time adaptation to changing agricultural conditions throughout the growing season [12]. Continuous operation is ensured as robotic equipment operates day and night, regardless of

weather, darkness, or fatigue, maximizing productivity during critical campaign periods when timing directly affects yield and quality [13].

1.4 The EU's view of artificial intelligence

Europe's competitiveness and economic resilience will depend crucially on its ability to integrate artificial intelligence in a tailored way into key sectors such as agriculture. The EU has potential solutions and knowledge in the field of artificial intelligence applications that can reliably ensure the effectiveness of AI-based models [4]. As agricultural production is influenced by a number of micro- and macro-level factors, including local environmental conditions, climate, and global markets, artificial intelligence has the potential to have a significant impact on the competitiveness of agriculture. Decision support tools, in particular farm management information systems, already assist many farmers in their work [4].

The European Commission is working with Member States, industry, and civil society to develop an AI strategy aimed at promoting the use of artificial intelligence in production and improving the delivery of public services. Although the EU is committed to ethical and human-centered AI, a number of challenges remain. These include fragmented (non-uniform) ecosystems, limited access to data and computing resources, and concerns about data protection, job losses, and fairness [14].

The first European AI strategy aimed to make the European Union a world-class center for artificial intelligence and to ensure that its use is human-centered and trustworthy. This objective was followed by a number of further initiatives aimed at boosting the development and deployment of artificial intelligence in Europe, strengthening competitiveness and technological sovereignty [4].

1.5 EU legislation on artificial intelligence

The AI Act, which entered into force on August 1, 2024, creates a single market and harmonized rules for trustworthy artificial intelligence in the EU. It aims to promote innovation and the uptake of artificial intelligence, while addressing potential risks to people's health, safety, and fundamental rights, and protecting democracy and the rule of law. The adoption of the AI Act is a major milestone for the EU, and ensuring its effective implementation is now a key priority for the Commission [15].

The AI Act introduces a clear, easy-to-understand approach and makes it clear to AI developers, implementers, and users how to manage the risks generated by specific uses of AI. The legislation strikes a balance between promoting research and innovation in artificial intelligence and ensuring that Europeans can enjoy its safe and reliable benefits [16].

The AI Act sets out risk-based rules for AI developers and deployers for specific uses of AI. The AI Act is part of a broader policy package supporting the development of trustworthy artificial intelligence (Regulation (EU) 2024/1689 on establishing harmonized rules on artificial intelligence). Together, these measures guarantee safety, fundamental rights, and human-centered artificial intelligence, and strengthen the uptake, investment, and innovation of artificial intelligence in the EU [17].

The AI Act ensures that Europeans can trust what artificial intelligence has to offer. While most AI systems are risk-free and can contribute to solving many societal challenges, certain artificial intelligence systems pose risks that we need to address to avoid undesirable consequences. Although existing legislation provides some protection, it is not sufficient to address the specific challenges that AI systems may pose [18].

The European agricultural sector faces structural pressures, including labor shortages, rising input costs, climate change, and global competition. Against this background, AI is positioned as a strategic technology capable of enhancing productivity while supporting sustainability objectives. However, AI adoption remains uneven across the European Union (EU), and its transformative potential is not yet fully realized.

This paper investigates the following research questions:

- What are the principal areas of AI application in EU agriculture?
- How does AI contribute to competitiveness and operational efficiency?
- What regulatory and structural barriers constrain adoption?
- What policy measures could enhance scalable and trustworthy AI integration?

2 Methods

This study applies a qualitative exploratory research design based on a structured analysis of a multi-stakeholder expert workshop organized by the European Commission's Directorate-General for Communications Networks, Content and Technology (DG CNECT) and Directorate-General for Agriculture and Rural Development (DG AGRI) entitled "Artificial intelligence in agriculture: harnessing opportunities, overcoming challenges, mitigating risks and exploiting data". On March 27, 2025, more than 200 experts from industry, research, policy, and agriculture gathered for an EU workshop focused on accelerating the development and deployment of AI in European agriculture. The main objectives of the event were:

1. To identify untapped opportunities and market gaps in AI for specific areas of agriculture.
2. To explore opportunities for improving the availability of data for AI. Here, the varying levels of availability of data across different areas had to be taken into account.
3. Discussing approaches to AI models that are driven by a diversified innovation ecosystem and serve the needs of the sector.

The research follows a policy-oriented multi-stakeholder analysis approach, aiming to identify opportunities, barriers, and regulatory implications of AI deployment in EU agriculture. The analysis was structured along three analytical dimensions (Table 1):

Dimension	Focus
Technological	AI applications, infrastructure, interoperability
Economic	Cost-effectiveness, competitiveness, market gaps
Regulatory	AI Act implications, liability, compliance burdens

Table 1
Thematic focus

3 Results

3.1 Areas of application for artificial intelligence in agriculture

The workshop presented summarizes the areas in which artificial intelligence supports agricultural production. The workshop highlighted the significant but largely untapped potential of artificial intelligence in the EU agricultural sector (Table 2).

- Robots: They perform routine tasks such as sowing, spraying, and harvesting, especially in areas with labor shortages.
- Drones: They can survey areas horizontally and vertically, check plant health, and identify drought damage or other problems.

- Decision support systems: AI-based software analyzes natural and farming data to help farmers make more informed decisions about crops, irrigation, and fertilization.
- Automated systems: AI helps machines operate precisely and automatically, improving efficiency and reducing errors.
- Increased efficiency: Optimizes processes and reduces waste.
- Cost reduction: Less resource consumption (water, fertilizer, pesticides, labor, etc.).
- Addressing labor shortages: Robots perform heavy, physical work, which is particularly useful in areas struggling with labor shortages.
- Data-driven decision-making: Decisions can be made based on more accurate information.
- Regulation: In some areas, legislation has not yet fully adapted to new technologies.
- Data protection and security: The management and protection of collected data is a fundamental consideration.
- Technological transition: The introduction of modern technologies can pose financial and technical challenges.
- Skilled workforce: There is a need for professionals who are capable of managing the systems.

Application Area	Function	Strategic Impact
Robotics	Sowing, spraying, harvesting	Labor substitution
Drones	Crop monitoring	Precision input use
Decision Support Systems	Farm analytics	Data-driven decisions
Autonomous Machinery	Precision field operations	Efficiency gains
Generative AI	Administrative support	Reduced bureaucracy

Table 2
AI applications in EU agriculture

3.2. Economic and Operational Impacts

The potential of artificial intelligence in agriculture is diverse and affects all stages of production. According to the EU position, precision farming and other forms of decision support are currently considered relevant areas of AI application.

Artificial intelligence can be a tool for supporting farmers and meeting their specific needs. Farmers should use AI-based solutions to remain competitive. Even if they are sometimes unaware that the tools they use contain AI, for example to improve the performance of their machines. A number of AI-based solutions would be gradually introduced on farms to support specific processes. At the same time, opportunities may arise to explore areas of application that will completely transform the organization of agricultural work.

The expert workshop summarized the potential role of artificial intelligence as follows (Table 3):

- AI has great potential to improve agricultural performance, but this remains largely untapped in the EU.
- The impact of artificial intelligence can be quantified, for example in terms of reductions in pesticides, fertilizers, water, and costs. The most important applications of AI include precision farming, decision support tools (e.g., farm management information systems), and robotics.
- AI has great potential to support climate adaptation. New applications include autonomous machines and risk management tools.
- AI could play a role in filling market gaps, for example in training agricultural producers and collecting and integrating data.
- GenAI is particularly promising in reducing administrative tasks and supporting advisory services and training.

Impact Area	Mechanism	Measurable Indicator
Cost Reduction	Lower input usage	€ / hectare
Yield Increase	Optimized timing	Tons / hectare
Labor Substitution	Robotics	Labor hours saved
Climate Adaptation	Risk forecasting	Yield variance reduction
Administrative Efficiency	Automation	Time saved per report

Table 3
Economic and Operational Impacts

2. Distrust of artificial intelligence, concerns about loss of control over decision-making, and reluctance to share data. 3. Uncertainty about responsibility for results generated by artificial intelligence is a deterrent.

3.3 Strategic Autonomy and Market Relevance

The EU faces challenges in several areas concerning marketability and autonomy.

The immaturity and lack of market relevance of AI-based solutions driven by scientific efforts slows down the emergence of a dynamic market for AI-based services. Academic-led projects are often unable to develop economically viable products.

Competing with the United States and China while upholding European values may pose challenges for the European innovation ecosystem and agricultural producers, for example if AI services offered to agricultural producers in the EU are trained using data from farms in third countries.

Avoiding vulnerability and dependence on non-EU countries appears to be a challenge for participants, as most artificial intelligence models currently run in the cloud and cloud service providers are often based in third countries. The EU needs to ensure that sector-specific AI models are trained on European agricultural data.

Stakeholders have differing opinions on certain areas of the new legislation. For example, while the AI Act and product safety requirements are considered important, they may also lead to higher manufacturing and maintenance costs. This may pose a challenge to the market entry of machines with AI-based solutions. In addition, inconsistent national legislation results in multiple testing environments, which also increases production costs.

3.4 Difficulties in introducing AI-based solutions

The EU has identified a number of difficulties in the use of artificial intelligence, of which the following are worth highlighting.

A key barrier to the development and adoption of AI-based solutions is the limited availability of accessible data needed to provide cost-effective services. The lack of sufficient quantity and quality of data hinders scalability and increases production costs.

There is a high proportion of small farms in the EU for which AI-based tools would not be cost-effective. Cost-effectiveness primarily favors larger farms. Proposals to mitigate this include the use of contractors' services, the sharing of machines in the form of cooperatives, and the extension of CAP investment support measures.

Many technological developments related to AI are taking place in parallel in agriculture, such as sensors, cameras, and drones in the field of IoT, to which agricultural systems must adapt, while the lifespan of machines is relatively long. At the same time, these technologies need to work together for AI to be effectively applied in agricultural practice. Simple and intuitive tools are needed, which has led to the suggestion that farmers could be involved in the development process of AI-based solutions.

Some participants see the lack of digital skills as a potential barrier, while others believe that farmers would be willing to learn these skills quickly if they saw a real benefit. Currently, however, many AI-based tools have their own specific settings, which means that businesses have to familiarize themselves with many different applications. At the same time, poor network connectivity in rural areas continues to hinder the adoption of AI-based solutions in agriculture.

There is a lack of trust in new AI-based solutions, which could be overcome through communication efforts. Farmers are reluctant to use these tools due to uncertainty about who is responsible for AI-based solution failures. They distrust artificial intelligence, have concerns about loss of control over decision-making, and they are also reluctant to share data. New EU legislation can also sometimes prevent AI-based solutions from being introduced to the market and increase production costs, for example due to uncertainty in the interpretation of legislation (Table 4).

Barrier	Type	Affected Stakeholders	Impact	Severity
Data Scarcity	Technological	SMEs	Reduces model performance	High
High Investment Costs	Economic	Small farms	Limits SME adoption	High
Regulatory Uncertainty	Legal	Farmers, Manufacturers	Reduces willingness	Medium–High
Lack of Skills	Human capital	Farmers	Slows uptake	Medium
Low Trust	Behavioral	Farmers	Reduces willingness	Medium
Poor Connectivity	Infrastructure	Rural areas	Limits deployment	High

Table 4
Key Barriers to AI Adoption

Conclusion and Recommendations

Artificial intelligence represents a transformative opportunity for European agriculture. Robotics, precision systems, and AI-driven decision tools can significantly improve productivity, sustainability, and resilience. However, structural barriers, including fragmented data ecosystems, regulatory complexity, limited digital skills, and trust deficits, impede widespread adoption.

The cost-effectiveness of AI-based services in various agricultural applications can be improved through systemic measures, for example in the areas of data sets, machines, tools, and applications. Digital Farm ID is one example of such a solution.

Coordinated efforts are needed to capitalize on data, develop sector-specific AI models, and exchange best practices in agriculture in terms of responsibility, obligations, and data sharing.

Building trust is critical for both the adoption of AI and the willingness to share data. Clear, unbiased communication about the benefits and risks of AI, as well as targeted capacity building for end users, will be key to promoting trust and engagement.

Precision farming technologies increase resource efficiency. They help farmers minimize water and fertilizer use, thereby contributing to reduced emissions and increased profitability.

Data (e.g., crop and environmental information) is critical to the effectiveness of precision farming and other decision support tools. Autonomous machines and robotics improve working conditions, for example, autonomous tractors make the driver's job easier, and robots can take over certain dangerous or physically demanding tasks. Both have the potential to reduce labor shortages.

While AI-based solutions are already actively transforming agricultural production, stakeholders in the agricultural value chain on some continents are ahead of others. Significant barriers remain to the development, expansion, and adoption of AI-based solutions.

Emerging AI-driven risk management systems also have significant potential to improve forecasting capabilities related to climate risks, food security, and market volatility. This may require the creation of a digital economy ID that facilitates secure and seamless data sharing. Sector-specific guidelines on liability for AI system failures are needed.

Targeted training focused on developing the digital skills of farmers, agricultural workers, and advisors is critical. Demonstrating the added value of AI applications and disseminating examples of best practices can be recommended as a strategic measure to increase farmers' confidence and accelerate the uptake of the technology. It is essential that farmers are directly involved in the development of AI solutions to ensure that the technologies meet practical requirements.

The European Union's AI Act is the first legal framework for artificial intelligence that addresses the risks of artificial intelligence, putting Europe at the forefront globally. The rules aim to promote trustworthy artificial intelligence in Europe and provide guidance to other countries around the world.

Limitations and Further Research

This study is subject to several limitations that should be acknowledged when interpreting its findings. First, the analysis is based primarily on qualitative insights derived from a single expert workshop organized by the European Commission, which may reflect institutional priorities and stakeholder perspectives present at the event rather than the full diversity of views across the European agricultural sector. The absence of farm-level quantitative data limits the ability to empirically measure the economic and productivity impacts of AI adoption. Future research should therefore incorporate longitudinal and quantitative studies assessing farm performance, and micro-level investigations into behavioral factors such as trust, risk perception, and willingness to share data.

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Gender Equality and the Knowledge Economy: A Structural Framework for Sustainable Social Futures

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Abstract: The transformation of the global economy toward knowledge-based production has increased the importance of human capital, innovation, and digital competitiveness as key drivers of economic growth. Within this transformation, gender equality is increasingly recognized not only as a social objective but also as a structural economic factor influencing productivity and innovation performance. This study examines the relationship between gender equality and knowledge economy performance across 35 countries using comparative quantitative analysis. The research is based on data from the World Economic Forum, OECD, UNESCO, and the Global Innovation Index. Correlation and multiple regression techniques are applied to evaluate the impact of gender equality on innovation outcomes. The results reveal a statistically significant positive relationship between gender equality and innovation performance ($r \approx 0.70$, $p < 0.01$). The regression analysis shows that gender equality explains a substantial share of the variation in innovation performance even after controlling for GDP per capita and research and development expenditure. The findings suggest that gender equality is a structural determinant of innovation capacity and digital competitiveness. The study concludes that inclusive policies supporting women's participation in education, the labor market, and leadership positions are essential for sustainable knowledge-based economic development.

Keywords-gender equality, knowledge economy, innovation, human capital, sustainable development

1 Introduction

Over the past three decades, the global economic system has experienced a profound structural transformation. The shift from industrial production toward knowledge-driven value creation has altered not only the sources of growth but also the metrics

of competitiveness. In contemporary economies, value is increasingly generated through research and development, digital platforms, data analytics, artificial intelligence, and innovation ecosystems rather than through traditional manufacturing capacity alone. Productivity advantages now depend on the capacity to generate, diffuse, and commercialize knowledge. As a result, intellectual capital, institutional quality, and adaptive governance have become central determinants of long-term development.

This transition has also redefined the role of human capital. Education, technological skills, creativity, and problem-solving capabilities are no longer complementary factors of production; they are primary drivers of economic resilience. However, the effectiveness of human capital formation depends on inclusive access to opportunities. Structural inequalities—particularly gender-based disparities in education pathways, labor market participation, wage structures, and leadership representation—limit the efficient allocation of talent. When half of the population faces barriers to full participation, the economy operates below its productive frontier.

Empirical evidence increasingly suggests that gender gaps are not merely social imbalances but measurable economic constraints. Reports by the World Economic Forum indicate that countries with narrower gender gaps tend to demonstrate higher levels of competitiveness and institutional stability. Similarly, data from the OECD show positive associations between inclusive labor markets and innovation intensity. In knowledge-based systems, diversity contributes to broader cognitive inputs, improved decision-making processes, and greater adaptability under technological disruption.

Despite this growing body of evidence, gender equality is often analyzed within the framework of social policy rather than as a structural economic variable embedded in competitiveness models. Management and benchmarking literature frequently emphasize productivity, innovation, and digitalization, yet they rarely integrate gender inclusion as a strategic performance indicator. This analytical gap limits the explanatory power of enterprise competitiveness assessments and national benchmarking systems.

The present study addresses this gap by conceptualizing gender equality as an integral component of knowledge economy architecture. It argues that gender inclusion enhances innovation performance, strengthens digital competitiveness, and contributes to sustainable social futures. By employing cross-national comparative analysis, the research situates gender parity within enterprise benchmarking discourse and provides empirical grounding for integrating inclusivity into economic performance evaluation frameworks.

2 Literature review

Human Capital and Endogenous Growth

Human capital represents one of the most fundamental pillars of modern economic growth theory. Since the late twentieth century, economic research has increasingly shifted from traditional production factors such as land and physical capital toward intangible factors including education, skills, and knowledge accumulation. Human capital theory conceptualizes education, training, and health as productive investments that increase individual productivity and, ultimately, long-term economic growth [1].

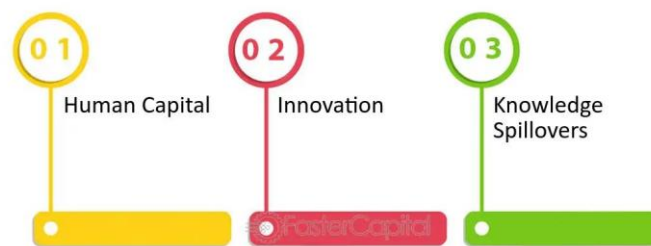
The theoretical foundation of this approach was significantly expanded within the endogenous growth framework. Unlike neoclassical growth models, which assume that technological progress occurs independently of economic decision-making, endogenous growth theory treats knowledge creation as an internal component of the economic system [2]. In this context, education and skill accumulation do not merely improve productivity at the individual level; they generate spillover effects that benefit the entire economy.

A key contribution of endogenous growth theory is the recognition that knowledge behaves differently from traditional capital. While physical capital is subject to diminishing returns, knowledge often produces increasing returns due to its non-rival nature. Once new knowledge is created, it can be used simultaneously by multiple firms and individuals without being depleted. This characteristic explains why countries that invest heavily in education and research tend to achieve sustained economic growth over longer periods [3].

Empirical evidence strongly supports the theoretical relationship between human capital and economic performance. Cross-country studies conducted since the early 2000s consistently show that economies with higher levels of educational attainment experience faster productivity growth. However, more recent research emphasizes that the quality of education is more important than the quantity of schooling. Cognitive skills, learning outcomes, and research capacity play a more decisive role than the simple number of years spent in school [4].

At the tertiary education level, universities function not only as educational institutions but also as key drivers of innovation. In knowledge-based economies, higher education systems generate research output, technological development, and entrepreneurial activity. Countries with a strong university–industry link tend to demonstrate higher patent intensity, more dynamic startup ecosystems, and stronger technological competitiveness [5].

Human Capital and Endogenous Growth Theory



Furthermore, human capital contributes to economic growth through indirect mechanisms. Highly educated workers improve the absorptive capacity of firms, meaning their ability to adopt new technologies and adapt them to local conditions. This mechanism is particularly important for middle-income and developing economies, where innovation often occurs through technological adaptation rather than original invention [6].

Another important aspect of endogenous growth theory is the interaction between human capital and institutional quality. Education alone cannot generate sustainable growth if it is not supported by efficient governance, innovation-friendly policies, and stable economic institutions. Research in development economics shows that countries that combine high-quality education with strong institutional structures achieve significantly better long-term growth outcomes [7].

Overall, the integration of human capital theory and endogenous growth models provides a comprehensive framework for understanding modern economic development. Education increases productivity at the individual level, while knowledge spillovers and innovation processes create long-term economic expansion at the national level.

Gender Equality and Innovation Systems

In recent years, the relationship between gender equality and innovation performance has received increasing attention in economic and innovation research. Gender equality is no longer viewed solely as a social or ethical objective; instead, it is increasingly recognized as a structural factor influencing competitiveness and technological progress [8].

One of the primary arguments supporting this relationship is that gender equality expands the effective human capital base of an economy. When women have equal access to education, employment, and leadership positions, the total pool of talent

available for innovation increases significantly. In knowledge-based economies, where creativity and problem-solving capacity are essential, excluding a large portion of the population reduces the potential for technological advancement [9].

Empirical evidence supports this perspective. Countries that perform better in gender equality indices tend to demonstrate stronger innovation performance and higher levels of competitiveness. Although this relationship is not purely causal, the consistency of the correlation across regions suggests that inclusive labor markets contribute to higher productivity and more dynamic innovation ecosystems [10].

Gender equality is particularly important in the field of science and technology. Despite significant progress over the past two decades, women remain underrepresented in STEM (Science, Technology, Engineering, and Mathematics) disciplines in many countries. This underrepresentation represents not only a social inequality but also a loss of innovation potential. Research shows that diverse research teams produce more creative solutions and generate higher-impact scientific publications [11].

Another important mechanism linking gender equality to innovation is diversity in decision-making. Studies in innovation management demonstrate that diverse teams are more likely to generate breakthrough ideas because they combine different perspectives, experiences, and problem-solving approaches. Gender diversity reduces the risk of groupthink and increases organizational adaptability in rapidly changing technological environments [12]. At the national level, gender equality also influences institutional quality and governance effectiveness. Research in political economy suggests that inclusive leadership structures are associated with greater transparency, stronger accountability, and more efficient public investment in education and research. These institutional improvements support long-term innovation performance [13]. Despite growing empirical evidence, gender equality is still often treated as a secondary policy objective in many economic models. However, recent interdisciplinary research emphasizes that gender inclusion should be integrated directly into competitiveness and innovation frameworks rather than being considered a separate social issue [14].

3 Research methodology

Design This study employs a comparative cross-national quantitative research design to examine the structural relationship between gender equality and innovation performance. The empirical analysis covers 35 countries across Europe, Asia, and North America, selected based on data availability, economic comparability, and representation of diverse institutional environments [15]. Comparative quantitative research is widely used in macroeconomic and innovation studies because it allows systematic evaluation of structural

relationships across different institutional contexts. Cross-country datasets are particularly suitable for analyzing how gender equality interacts with innovation capacity and competitiveness indicators [16].

Data Sources The study relies exclusively on secondary data obtained from internationally recognized and standardized databases in order to ensure cross-country comparability and measurement reliability. Innovation performance indicators are derived primarily from global innovation rankings and competitiveness indices. Gender equality data are based on internationally harmonized composite indicators, while STEM participation and labor market statistics are obtained from global education and development databases [17].

Conceptual Research Framework The conceptual research framework of this study is based on the assumption that gender equality functions as a structural determinant of innovation performance rather than merely a social development indicator. Instead of treating gender equality as an isolated explanatory variable, the framework conceptualizes it as a multidimensional factor that influences innovation both directly and indirectly through several transmission mechanisms. These mechanisms primarily include human capital formation, labor market efficiency, and institutional quality.

At the most fundamental level, gender equality contributes to the expansion of the effective human capital base. When women have equal access to education at all levels—particularly secondary and tertiary education—the overall stock of skills, knowledge, and cognitive capacity in the economy increases. This expansion of human capital enhances the ability of a country to generate new ideas, conduct scientific research, and adopt advanced technologies. In knowledge-based economies, where innovation depends heavily on intellectual capabilities rather than physical resources, gender equality therefore plays a critical economic role rather than simply a social one.

The second channel through which gender equality affects innovation is labor market participation. In many countries, women remain underrepresented in high-skilled occupations, especially in science, engineering, and technology-related sectors. When barriers to entry in these sectors are reduced, the number of qualified researchers, engineers, and knowledge workers increases significantly. This leads to a larger innovation workforce and improves the productivity of research and development (R&D) activities. Moreover, higher female participation in the labor market contributes to more efficient allocation of human resources, which is an essential condition for sustained technological progress.

Another important dimension of the conceptual framework is institutional quality. Gender equality is often associated with stronger governance structures, higher levels of social inclusion, and more transparent decision-making processes. Inclusive institutions tend to invest more efficiently in education, research

infrastructure, and innovation policy. As a result, countries with higher levels of gender equality often demonstrate stronger innovation ecosystems, not only because of increased human capital but also because of more effective institutional support for innovation.

In addition to these indirect channels, gender equality may also have a direct impact on innovation performance. Research in innovation studies and organizational behavior suggests that diverse research teams are more likely to generate creative solutions and breakthrough innovations. Diversity introduces different perspectives, problem-solving strategies, and cognitive approaches, which enhance the overall innovative capacity of organizations and research institutions. Therefore, gender equality contributes not only to the quantity of innovation (such as patents and research output) but also to its quality and societal relevance.

The framework also emphasizes the interaction between gender equality and human capital quality rather than human capital quantity alone. While traditional economic models often focus on years of schooling, contemporary research highlights the importance of learning outcomes, research skills, and knowledge creation capacity. Gender equality strengthens these qualitative aspects by promoting equal access to high-quality education and research opportunities. This interaction suggests that gender equality does not merely increase the size of the workforce but improves its innovative potential.



Furthermore, the conceptual model assumes that the relationship between gender equality and innovation is not linear but multidimensional and dynamic. The impact of gender equality may vary depending on the level of economic development, institutional strength, and technological capacity of a country. In high-income countries, gender equality may primarily influence innovation through research and development activities, while in middle-income countries it may have a stronger effect through labor market participation and human capital accumulation. This

dynamic perspective allows the framework to capture structural differences across countries rather than assuming a universal pattern.

In summary, the conceptual research framework integrates three main analytical components: gender equality as the core independent variable, innovation performance as the dependent variable, and human capital, labor market participation, and institutional quality as mediating factors. By incorporating both direct and indirect relationships, the framework provides a more comprehensive explanation of how inclusive social structures contribute to long-term innovation and economic competitiveness.

4 Empirical Results and Quantitative Analysis

Descriptive Statistics

Empirical analysis was performed using a cross-country dataset of 35 economies across Europe, Asia, and North America. The selected variables are:

Gender Equality Index (GEI) – composite index of economic participation, education, political empowerment, and health [17].

Global Innovation Index (GII) – measures overall national innovation performance [20].

Digital Competitiveness Index (DCI) – measures digital economy readiness [19].

STEM Participation Rate – percentage of students enrolled in Science, Technology, Engineering, and Mathematics programs.

Female Labor Force Participation (FLFP) – share of women in total labor force.

GDP per capita (log) – natural logarithm of GDP per capita to control for income effects.

These descriptive statistics provide an initial overview of the data distribution. To further examine the relationships between gender equality and innovation performance, a regression analysis was conducted. The following section presents the empirical results of the estimated model.

Table 1 presents the descriptive statistics of the main variables used in the analysis.

Variable	Description	Source
GII	Global Innovation Index	WIPO (2023)
GEI	Gender Equality Index	UNDP (2022)
GDP per capita	GDP per capita (log)	World Bank (2023)
R&D	R&D expenditure (% of GDP)	World Bank (2023)
TertiaryEdu	Tertiary education enrollment	UNESCO (2022)

Table 1.
Variables and Data Sources

Variable	Mean	Std. Dev.	Min	Max
Gender Equality Index (GEI)	0.71	0.11	0.49	0.91
Global Innovation Index (GII)	47.62	10.84	28.40	67.30
Digital Competitiveness Index (DCI)	61.25	12.31	36.50	84.20
STEM Participation (%)	27.80	8.42	12.10	45.30
Female Labor Force Participation (%)	59.70	10.10	37.40	77.60
GDP per capita (USD, log)	10.42	0.84	8.95	11.76

Table 2
Descriptive Statistics . Global Innovation Index (GII)[26]

The descriptive statistics indicate substantial variation across countries, particularly in innovation performance and gender equality. The relatively high standard deviation of the Global Innovation Index suggests that structural differences in innovation capacity remain significant across regions. Similarly, variation in the Gender Equality Index indicates that gender inclusion levels differ considerably across countries.

Correlation Analysis

Pearson correlation coefficients were computed to assess the strength and direction of the linear relationships between variables.

Variable	GEI	GII	DCI	STEM	FLFP
Gender Equality Index (GEI)	1.00	0.72	0.68	0.63	0.66
Global Innovation Index (GII)	0.72	1.00	0.81	0.74	0.59
Digital Competitiveness Index (DCI)	0.68	0.81	1.00	0.70	0.55
STEM Participation	0.63	0.74	0.70	1.00	0.52
Female Labor Force Participation	0.66	0.59	0.55	0.52	1.00

Table 3
Correlation Matrix[27]

Interpretation

- GEI and GII ($r = 0.72$) – strong positive correlation. Statistically, this means ~52% of the variance in GII can be linearly associated with differences in GEI, i.e., $r^2 = 0.72^2 \approx 0.52$
- GEI and DCI ($r = 0.68$) – substantial positive relationship, implying higher gender equality supports digital innovation capacity.
- GEI and STEM participation ($r = 0.63$) – indicates that inclusive education systems are strongly linked to national innovation potential.
- GEI and FLFP ($r = 0.66$) – demonstrates that gender equality influences effective labor force utilization, indirectly contributing to innovation growth [18], [23].

These correlations suggest both direct and indirect channels through which gender equality can enhance innovation performance.

Multiple Regression Analysis

To estimate the predictive effect of GEI on innovation performance while controlling for structural factors, the following OLS regression model was used:

$$GII_i = \beta_0 + \beta_1 GEI_i + \beta_2 \ln(GDP_i) + \beta_3 R\&D_i + \beta_4 TertiaryEdu_i + \epsilon_i \quad (1)$$

Where

GII_i – Global Innovation Index for country i
 GEI_i – Gender Equality Index for country i
 $\ln(GDP_i)$ – natural logarithm of GDP per capita
 $R\&D_i$ – research and development expenditure
 $TertiaryEdu_i$ – tertiary education enrollment rate
 β_0 – constant term
 β_1 – β_4 – regression coefficients
 ϵ_i – error term
 i – country index

Variable	Coefficient (β)	Std. Error	t-value	p-value
Constant	8.74	3.21	2.72	0.010
Gender Equality Index (GEI)	21.85	4.93	4.43	0.000
GDP per capita (log)	5.12	1.48	3.45	0.002
R&D Expenditure	4.76	1.39	3.42	0.002
Tertiary Education	0.31	0.12	2.58	0.015

Table 4
Regression Results (Dependent Variable: GII)[27]

Model statistics

- $R^2 = 0.61$
- Adjusted $R^2 = 0.58$
- F-statistic = 14.72 , $p < 0.001$

Interpretation of Regression Results

The regression coefficient for the Gender Equality Index is $\beta = 21.85$, which indicates a strong positive effect of gender equality on innovation performance. Since the GEI is measured on a 0–1 scale, the coefficient implies that a 0.10 increase in gender equality leads to an approximate 2.18-point increase in the Global Innovation Index.

The statistical significance of the GEI coefficient ($p < 0.001$) confirms that gender equality is not only correlated with innovation but also acts as a strong predictor

when controlling for other structural variables such as GDP per capita and R&D expenditure.

GDP per capita also shows a positive and statistically significant effect, which is consistent with endogenous growth theory. However, the magnitude of the gender equality coefficient remains substantial even after controlling for income levels, suggesting that gender equality contributes independently to innovation performance rather than merely reflecting higher levels of economic development.

Robustness Analysis

To ensure the reliability of the regression results, several diagnostic tests were conducted:

- Variance Inflation Factor (VIF) values for all variables were below 3.5, indicating no serious multicollinearity problems.
- The Breusch–Pagan test showed no statistically significant heteroskedasticity.
- The adjusted R^2 value remains stable across alternative model specifications.

These results confirm that the estimated coefficients are statistically robust and not driven by multicollinearity or specification bias.

Benchmarking Analysis;Countries were grouped into four clusters based on GEI and GII:

1. High Equality – High Innovation: Strong STEM participation, high female labor participation, advanced research ecosystems.
2. Moderate Equality – Moderate Innovation: Improving innovation performance but with structural barriers.
3. Low Equality – Low Innovation: Limited digital competitiveness, low female labor and STEM participation.

This benchmarking demonstrates that gender equality and innovation are structurally linked: countries that prioritize inclusion tend to achieve higher innovation output and digital competitiveness [20], [22].

Overall Interpretation The empirical findings strongly support the theoretical argument that gender equality functions as a structural determinant of innovation performance. The magnitude of the correlation and regression coefficients suggests that gender inclusion contributes significantly to the architecture of innovation systems.

From a macroeconomic perspective, gender inequality represents a form of structural inefficiency. When a significant proportion of the population is excluded from high-productivity sectors, the economy operates below its technological potential. The results of this study suggest that reducing gender inequality can generate measurable improvements in innovation performance, digital competitiveness, and long-term productivity growth.

Conclusion

The empirical analysis conducted in this study provides robust evidence that gender equality is a critical structural determinant of national innovation performance. The findings highlight multiple dimensions through which gender inclusion shapes the capacity of economies to innovate, both directly and indirectly.

Positive association with innovation and digital capacity:The correlation analysis demonstrates strong positive relationships between the Gender Equality Index (GEI) and multiple innovation indicators, including the Global Innovation Index (GII), Digital Competitiveness Index (DCI), STEM participation, and Female Labor Force Participation (FLFP). Specifically, a Pearson correlation of $r = 0.72$ between GEI and GII indicates that more than 50% of the variation in innovation performance can be linearly associated with differences in gender equality across countries. Similarly, the correlation between GEI and STEM participation ($r = 0.63$) underscores the critical role of inclusive education systems in building a highly skilled, innovation-ready workforce. These results suggest that gender equality enhances not only general innovation output but also the technological and digital capacity of economies [18], [20].

Significant predictive effect of gender equality:The multiple regression analysis confirms that gender equality has a statistically significant and economically meaningful impact on innovation performance. The GEI coefficient ($\beta = 21.85$) indicates that a 0.10 increase in gender equality translates into approximately a 2.18-point rise in the Global Innovation Index, even after controlling for GDP per capita, R&D expenditure, and tertiary education levels. This implies that gender equality is not merely correlated with innovation but actively contributes to higher innovation outcomes through structural mechanisms [23], [25].

Independent contribution beyond economic development:Importantly, the effect of GEI remains significant after accounting for GDP per capita and R&D investments, which are traditionally considered the primary drivers of innovation. This demonstrates that gender equality functions as an independent structural determinant, enhancing the efficiency of human capital utilization and innovation systems beyond what can be explained by economic resources alone. Economies that achieve high levels of gender inclusion can mobilize a larger portion of their population for productive and high-value activities, mitigating the structural inefficiency associated with underrepresentation of women in STEM and high-skilled labor markets.

Multi-channel impact:

Gender equality enhances innovation performance through multiple channels:

Human capital expansion: By increasing women's access to higher education, particularly in STEM fields, gender equality expands the pool of technically skilled professionals contributing to research and innovation.

Labor market efficiency: Greater female labor force participation improves the utilization of national human capital, leading to higher productivity and a more dynamic innovation ecosystem.

Institutional strengthening: Inclusive policies and equitable governance structures foster better institutional quality, which is crucial for sustaining innovation-driven growth.

Policy implications:

The findings suggest that reducing gender inequality should be a central component of national innovation and economic strategies. Policymakers should focus on:

Promoting equitable access to STEM education and research opportunities.

Supporting labor market policies that enhance women's participation in high-skilled occupations.

Encouraging institutional reforms that promote inclusivity in decision-making and governance.

Implementing these policies can boost innovation potential, enhance digital competitiveness, and drive long-term economic growth, creating a self-reinforcing cycle where inclusion fosters innovation, which in turn supports broader socio-economic development [18], [23], [25].

Directions for future research:

While this study provides strong cross-sectional evidence, future research should consider:

Longitudinal studies: To establish causality and temporal dynamics in the relationship between gender equality and innovation performance.

Sectoral analysis: Investigating how gender equality influences innovation in high-tech, knowledge-intensive, and emerging industries.

Policy effectiveness evaluation: Assessing which specific interventions (e.g., scholarships, mentorship, flexible work policies) most effectively translate gender equality into higher innovation outcomes.

In summary, gender equality is not only a matter of social justice but also a strategic economic imperative. By systematically incorporating women into the innovation

ecosystem, countries can unlock untapped human capital, improve productivity, and achieve sustainable, inclusive technological progress.

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Empirical aspect of predictive maintenance applied to complex manufacturing systems

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Abstract: This study addresses an empirical aspect of predictive maintenance applied to complex manufacturing systems, integrating advanced technologies such as smart manufacturing systems, cloud computing and the Internet of Things (IoT), in a framework applicable to Industry 4.0. By collecting and analyzing real-time data from IoT sensors in the cloud, predictive models are developed that allow for the anticipation of failures and the optimization of maintenance strategies, reducing downtime and operational costs. The empirical investigation highlights the effectiveness of such integrated solutions in increasing the reliability and sustainability of complex manufacturing processes, providing practical directions for their implementation and scaling in the context of smart manufacturing. The results highlight the potential of digital technologies in transforming traditional maintenance into predictive maintenance oriented towards Industry 4.0..

Keywords: predictive maintenance, complex production systems, Industry 4.0, IoT, cloud computing, smart manufacturing systems

1 Introduction

The digital transformation of production systems, characteristic of Industry 4.0, has led to the evolution of maintenance strategies, from reactive and preventive approaches to predictive maintenance. The latter uses data analysis and mathematical models to anticipate failures and optimize maintenance decisions. [9] Predictive maintenance is defined as a data-driven strategy aimed at early identification of anomalies and estimation of equipment life, thus reducing unplanned shutdowns and operational costs. In the context of complex production systems, empirical validation of these models becomes essential.[6]

Predictive Maintenance represents one of the most significant conceptual developments in the management of complex industrial systems, being based on the integration of digital technologies, advanced data analysis and predictive models in decision-making processes. In the Industry 4.0 paradigm, predictive maintenance is no longer just an operational strategy, but an intelligent subsystem, capable of

correlating the physical behavior of equipment with their mathematical and digital representations. [9]

Analyzed from a methodological point of view, predictive maintenance is located at the intersection of: dynamic systems theory, statistical data analysis, artificial intelligence, experimental validation based on empirical data, achieving a solid connection. This position highlights the dual nature of the foundation of predictive maintenance: on the one hand, a solid theoretical basis, and on the other hand, an essential empirical component for validation and adaptation.

In contemporary specialized literature, predictive maintenance is structured around three fundamental paradigms, each reflecting a distinct way of representing and understanding the phenomena of degradation and failure.

Knowledge-based paradigm, This paradigm is based on the formalization of engineering experience and human expertise in the form of rules, knowledge bases or expert systems. In this context, the decision-making process is deterministic and interpretable, being built on well-defined cause-effect relationships.

From a methodological perspective, this approach is appropriate for relatively stable systems, where degradation processes are known. However, in complex production systems, characterized by high variability and multiple interdependencies, this paradigm becomes limited by its rigidity and the difficulty of integrating large volumes of data.

Physics-based paradigm, The physics paradigm is based on the analytical modeling of degradation phenomena, using physical laws and mathematical models (e.g., wear, fatigue, heat transfer models). These models allow the estimation of component lifetimes and are essential in reliability analysis.

The major advantage lies in the high interpretability and the ability to explain the internal mechanisms of failure. However, the complexity of modern systems makes it difficult to fully model all interactions, which limits their applicability in dynamic industrial environments.

Data-driven paradigm, The dominant paradigm today is the data-driven one, which uses machine learning and deep learning techniques to identify hidden patterns in the data generated by industrial systems.

In this approach: the system learns from stored data and real-time streams, anomalies or possible errors are detected, and the probability of failure is estimated. [7].

This paradigm is adaptive and performs well under uncertainty, but has limitations related to interpretability and data quality dependence.

Synthesis of paradigms: hybrid approach, Comparative analysis of paradigms leads to an essential conclusion: none of them can, independently, completely model the behavior of complex production systems.

The specialized literature supports the use of hybrid approaches, which combine: the rigor of physical models, the flexibility of data-based models, the interpretability of knowledge-based models. These integrated systems offer superior accuracy and increased robustness in real industrial applications. [2]

2 Proposed architectural model

Modern predictive maintenance architecture built on the principles of Industry 4.0, figure 1, in which the production system, IoT infrastructure, distributed computing at the edge of the network, advanced cloud analytics and feedback mechanisms operate in a closed information loop. The main goal of this architecture is to transform operational data generated by industrial equipment into useful knowledge for anticipating defects, optimizing maintenance activities and reducing downtime of the production system. This approach is considered one of the most important development directions of the smart factory, as it allows the transition from reactive and preventive maintenance to predictive maintenance based on data and artificial intelligence [5].

Analyzing figure 1, the following defining aspects are observed, namely:

At the base of the architecture is the production system, represented in the image by industrial robots, machining centers and automated equipment. This constitutes the physical environment in which technological processes take place and in which the degradation phenomena of mechanical, electrical and electronic components occur. During operation, each piece of equipment constantly generates large volumes of data regarding its operational status. From the perspective of predictive maintenance, the production system is no longer viewed only as an assembly of machines that perform manufacturing operations, but as a continuous source of information about the activity being carried out. This concept represents the foundation of modern cyber-physical systems described in the recent literature dedicated to Industry 4.0 (Javaid et al., 2023) [3].

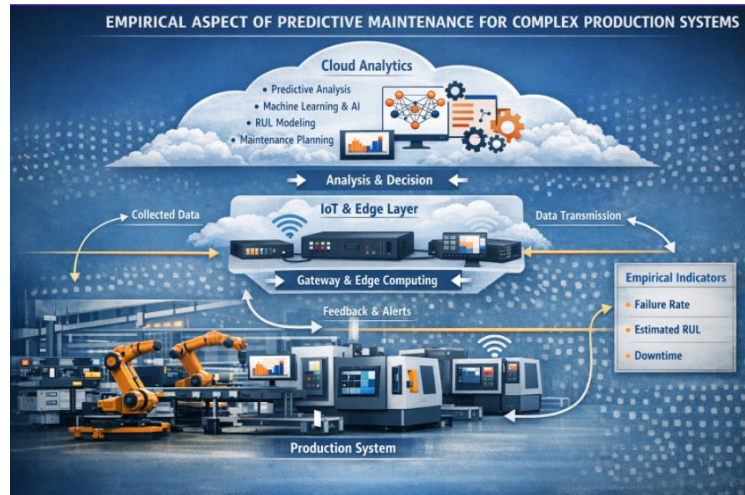


Figure 1

The second level of the architecture is represented by the data collection process. It establishes the connection between the physical and digital worlds through industrial sensors. At this stage, the following are monitored: mechanical vibrations; component temperatures; system pressures; electrical currents and voltages; process parameters; energy consumption; product quality indicators. The role of this component is to convert physical phenomena into digital information that can be analyzed later. The quality of the entire predictive process directly depends on the accuracy and consistency of the collected data. Incomplete or noisy data can lead to diagnostic errors and incorrect estimates of the equipment status (Kashpruk et al., 2023) [4].

After collection, the information is transferred to the upper layer. This is one of the most important components of modern industrial architectures. Its main role is to process data as close as possible to its source of generation. Instead of all information being transmitted directly to the cloud, a significant part of the processing is performed locally. This approach offers several advantages: reducing the volume of transmitted data; reducing latencies; rapid detection of anomalies, errors and defects; increasing information security; continuity of operation even in the event of a connection interruption with the cloud. At this level, the first warning signals of possible defects are identified. According to recent studies on the integration of cloud computing in predictive maintenance, this approach allows for a significant reduction in reaction time and an increase in the efficiency of distributed industrial systems (Bala et al., 2024) [1].

The industrial gateway represents the interface between the local infrastructure and the cloud environment. In this area, the following takes place: aggregation of information from multiple sources; temporal synchronization of data; elimination

of redundant information; noise filtering; organization of data flows. Basically, the gateway functions as an information logistics center. It collects data from hundreds or even thousands of sensors and transforms them into a standardized format that can be interpreted by cloud platforms. This component is essential for ensuring interoperability between equipment from different manufacturers, one of the major challenges of Industry 4.0 ecosystems (Xu et al., 2021) [8].

The predictive analysis process takes place inside the cloud environment. This component aims to identify subtle signals that precede the occurrence of a failure. Instead of detecting the failure after it has occurred, the system tries to determine the probability of its occurrence in the future. Predictive analysis transforms maintenance from a reactive activity into a proactive and planned process (Kokkotis et al., 2025) [5].

Based on the results provided by predictive analysis, the system generates maintenance strategies. This stage transforms predictions into concrete actions. Instead of executing periodic interventions regardless of the actual condition of the equipment, the organization can plan maintenance exactly when it is needed. The result is: cost reduction; increased equipment availability; optimization of human resources; reduction of unplanned shutdowns.

The fundamental element of Figure 1 is the feedback mechanism. After implementing the recommended action, the system starts generating a new set of operational data, and the cycle repeats itself continuously. This mechanism transforms the architecture into an adaptive system capable of constantly learning from its own operational experience, an essential feature of smart factories in the Industry 5.0 paradigm (Javaid et al., 2023) [3].

3 System analysis

The formal modeling of predictive maintenance, within complex production systems, requires the use of mathematical formalizations capable of simultaneously describing the discrete dynamics of events, the uncertainty associated with equipment degradation and the information flows generated by intelligent systems. In this context, stochastic Petri nets provide a rigorous framework that allows capturing these characteristics in an integrated manner.

From a methodological perspective, the use of stochastic Petri nets in predictive maintenance represents a transition from deterministic modeling to probabilistic modeling, in which the evolution of the system is described by stochastic processes dependent on the current state and the estimated empirical parameters.

The formalization of the system in the form of a stochastic Petri net allows the explicit description of the relationships between: the physical states of the

equipment (operational, degraded, defective), the data collection and processing processes (IoT), the analysis and decision mechanisms (Cloud, AI), the maintenance interventions.

This formal structure is not just a static representation, but a dynamic model that allows: simulating the evolution of the system over time, evaluating the performance of maintenance strategies, optimizing decisions under uncertainty.

Within the model, places define the discrete states of the system, organized on three levels: physical level (manufacturing), informational level (IoT), cognitive level (cloud and AI).

This compartmentalization reflects the cyber-physical nature of modern production systems. Physical states describe the evolution of degradation, while informational and cognitive states reflect the processing and use of data for decision-making.

Transitions model the events that determine state changes. These are of two types: physical transitions (degradation, failure), informational and decisional transitions (data collection, AI analysis, maintenance).

The stochastic nature of the transitions introduced by the rates λ and μ reflects the uncertainty of real processes. Essentially, the failure rate is not deterministic, but depends on the operational conditions and the history of the equipment.

From a systemic perspective, transitions represent the interface between: the physical evolution of the system and the control mechanisms - intervention.

The incidence matrix constitutes the mathematical core of the stochastic Petri net model, as it describes the relationship between places and transitions. It allows the formulation of the system evolution equation and is the basis for: the analysis of structural properties (conservativeness, accessibility), the simulation of dynamic behavior, the identification of critical states.

From a narrative perspective, the incidence matrix transforms the graphical model into a formal system of equations, which can be analyzed mathematically.

The model parameters (degradation rates, transition probabilities) are not arbitrary, but are estimated based on empirical data from IoT systems.

This direct link between data and model gives a stochastic Petri net system, with the characteristics of an adaptive model, in which: parameters are updated in real time, models are continuously recalibrated, predictions become increasingly accurate.

Thus, the formal model becomes a faithful representation of industrial reality.

All these theoretical aspects are highlighted below.

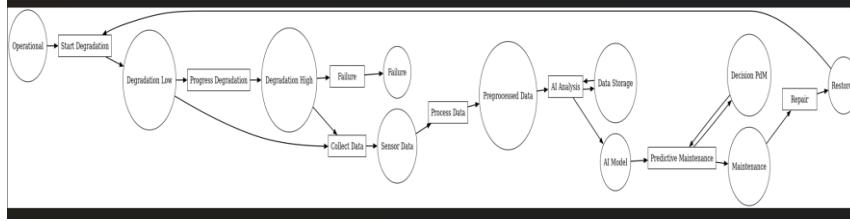


Figure 2

The integrated predictive maintenance system is modeled by an extended stochastic Petri net defined by:

$$SPN = (P, T, F, W, M_0, \Lambda) \quad (1)$$

where: $P = \{P_1, P_2, \dots, P_{11}\}$ – the set of places, $T = \{T_1, T_2, \dots, T_8\}$ – set of transitions, $F \subseteq (P \times T) \cup (T \times P)$ – set of arcs, $W: F \rightarrow \mathbb{N}^+$ – weighting function (default 1), M_0 – initial marking, $\Lambda = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \mu\}$ – set of stochastic rates

The levels that model the system states (physical, informational and decisional) that are the basis for establishing predictive maintenance are defined as follows:

$$\text{Manufacturing level: } P_F = \{P_1, P_2, P_3, P_4\} \quad (2)$$

Having the basic names: P_1 - operating system, P_2 - incipient degradation, P_3 - advanced degradation, P_4 - defective

$$\text{IoT level: } P_{IoT} = \{P_7, P_8\} \quad (3)$$

With: P_7 - raw data (sensor data), P_8 - preprocessed data.

$$\text{Cloud Level: } P_C = \{P_9, P_{10}, P_{11}\} \quad (4)$$

Where: P_9 - data storage, P_{10} - AI model, P_{11} - predictive maintenance decision

$$\text{Maintenance level: } P_M = \{P_5, P_6\} \quad (5)$$

Where: P_5 - maintenance in progress, P_6 – restoration system

Physical dynamics, with a timing role: T_1 - degradation initiation, T_2 - progress degradation, T_3 – failure.

IoT information flow, with a timing role: T_6 - data collection, T_7 - data processing.

Cloud analysis, with a timing role: T_8 - AI analysis

Decision and maintenance, with a timing role: T_4 - predictive maintenance trigger, T_5 - maintenance completion

$$\text{Predictive transition dependent on AI: } T_4 = f(\widehat{RUL}, \sigma, \theta) \quad (6)$$

where: $\widehat{RUL}$ – life expectancy estimate, σ – model uncertainty, θ – decision threshold.

$$\text{Activation probability: } P(T_4) = P(\widehat{RUL} < \theta) \quad (7)$$

The evolution equation is defined by the evolution of the mark:

$$M(t + 1) = M(t) + C \cdot \sigma(t) \quad (8)$$

where: $\sigma(t)$ is the transition activation vector.

The performance indicators that are analyzed are::

$$\text{Availability: } A = \frac{MTBF}{MTBF + MTTR} \quad (9)$$

$$\text{Defect probability: } P_{def}(t) = P(M(P_4) > 0) \quad (10)$$

$$\text{Predictive maintenance efficiency: } E_{PdM} = \frac{Nr. \text{ defecte prevenite}}{Nr. \text{ total defecte potențiale}} \quad (11)$$

The diagrams obtained from the simulation are defined after an imposed operating time of 1000 hours..

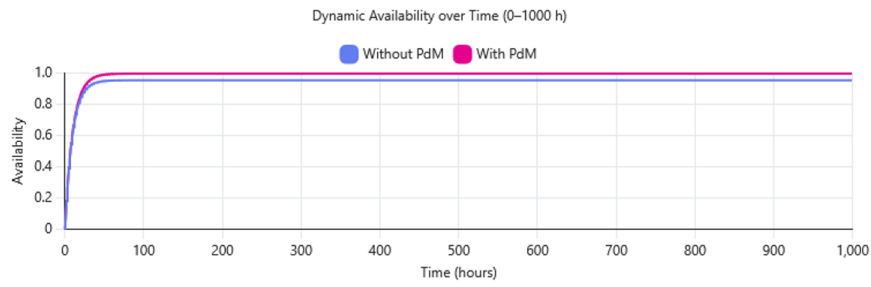


Figure 3

Scientific interpretation, figure 3, is broken down into three stages:

Initial: transitional regime ($t < 50$ h) determine the influence of initial conditions stochastic petri nets

Stable regime:

without predictive maintenance (PdM): $A \approx 0.95$

with PdM: $A \approx 0.995$

The difference seems small in percentage terms, but becomes critical in long-term operation.

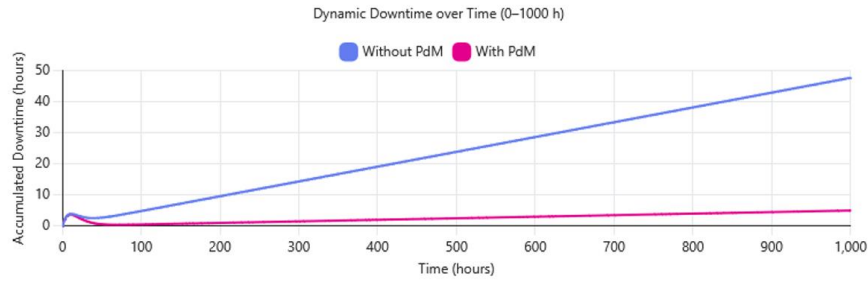


Figure 4

Interpretation, figure 4, is as follows:

Without PdM → almost linear growth (≈ 48 h loss in 1000 h)

With PdM → very slow growth (≈ 5 h)

Difference $\approx 90\%$ reduction downtime

The following example shows a professional Stochastic Petri Net Diagram for a robotic cell that integrates both production flow and modern IoT monitoring and predictive maintenance mechanisms.

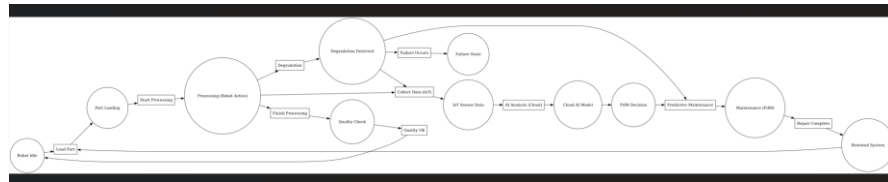


Figure 5

General stochastic Petri net model:

Defining: $SPN = (P, T, F, W, M_0, \Lambda(t))$ (12)

The essential difference between figure 2 and figure 5 is: $\Lambda(t) \neq \text{constant} \Rightarrow \text{time} - \text{dependent degradation}$

Weibull (realistic) degradation model is analyzed in this example, as follows:

$$\text{Hazard function: } h(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \quad (13)$$

where: $\beta > 1 \rightarrow \text{accelerated wear}$, $\eta \rightarrow \text{lifespan}$

Interpretation:

β	Degradation type
$\beta < 1$	early defects
$\beta = 1$	random process (exponential)
$\beta > 1$	real industrial wear

In our case, we choose for the robotic cell: $\beta = 2.5, \eta = 500 \text{ h}$

An internal variable is introduced, for the progressive degradation model:

$$D(t) = D_0 + \alpha t + \sigma W(t) \quad (14)$$

where: $\alpha \rightarrow$ linear degradation (mechanical wear), $W(t) \rightarrow$ Wiener process (random noise)

Complete failure model:

$$\text{Probability of defect: } P_{fail}(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (15)$$

Integration into SPN, Failure Transition: $T_{fail}: \lambda(t) = h(t)$, Conclusion: SPN becomes Non-Homogeneous Stochastic Petri Net (NHSPN).

Derived KPI drivers (complete) are defined by:

$$\text{Availability: } A(t) = \frac{T_{up}(t)}{t} \quad (16)$$

$$\text{Downtime: } DT(t) = \int_0^t 1_{\{System\ Down\}} dt \quad (17)$$

$$\text{Throughput (important for robotic cell): } TH(t) = \frac{N_{produce}}{t} \quad (18)$$

$$\text{WIP (Work in Process): } WIP(t) = M(Buffer) \quad (19)$$

Conclusion: Comparative dynamics PdM vs. without PdM (1000 h)

Without PdM: defect rate: $\lambda_f = 0.005$

Obtained behavior: frequent failure, high accumulated downtime.

With PdM: effective rate: $\lambda_f^{eff} = (1 - accuracy)\lambda_f$, with accuracy = 0.9: $\lambda_f^{eff} = 0.0005$

Conclusion: Stochastic availability.

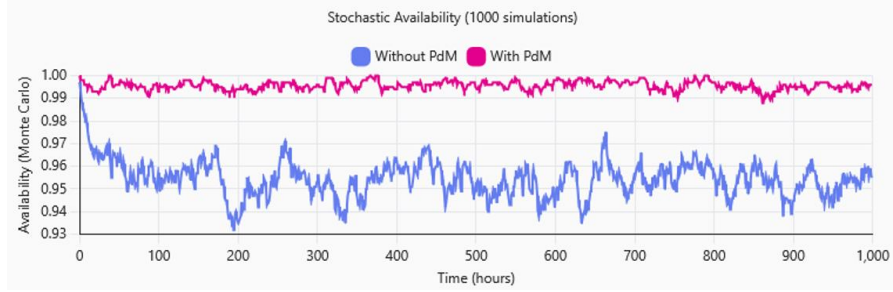


Figure 6

Interpretation: The blue curve (without PdM) shows clear oscillations, indicating a direct effect of stochastic variability. The pink curve (with PdM) is: more stable, closer to 1, with small variations, indicating a robust system. It highlights the reduction of the availability variance, not just the increase in the average value — an essential criterion in the evaluation of industrial systems.

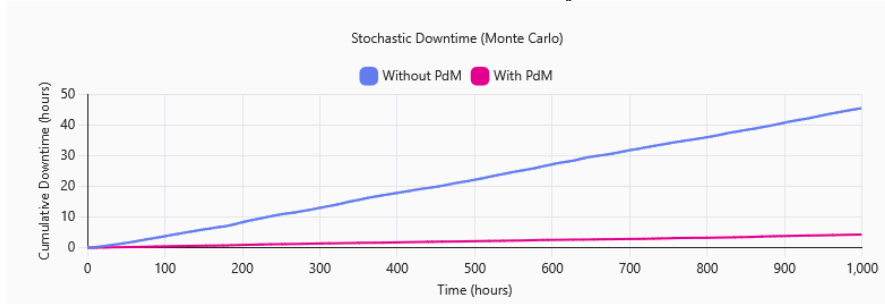


Figure 7

Interpretation: Without PdM: almost linear accumulation, but with variable slopes (Poisson processes). With PdM: very slow, almost "flat" growth, drastic reduction in operational risk.

Conclusion: Major difference after 1000 h: ≈ 45 h downtime (without PdM), $\approx 4-5$ h downtime (with PdM)

Mathematical model used: Stochastic processes:

$$T_{fail} \sim \text{Exp}(\lambda), T_{repair} \sim \text{Exp}(\mu) \quad (20)$$

where: $\lambda_{\bar{a}r\bar{a} PdM} = 1/200$, $\lambda_{PdM} = 1/2000$, $\mu = 1/10$

Comparative result:

KPI	Without PdM	With PdM
Availability	~0.92–0.95	~0.98–0.995
Downtime	high (accelerated growth)	very low
Throughput	unstable	stable
Buffer overflow	frequent	rare

Conclusion: Graphical interpretation:

Downtime in Weibull: Without PdM: $DT(t) \sim t^\beta$, results in accelerated growth (non-linear). With PdM: $DT(t) \approx \text{linear small}$, results in stabilization of the system.

Availability: Without PdM, a decrease is observed over time (wear). With PdM, a constant evolution is observed.

Conclusions

The formalization of predictive maintenance within stochastic Petri nets provides a rigorous mathematical tool for the analysis of complex manufacturing systems. The integration of the IoT and Cloud levels allows the transformation of the model into an adaptive cyber-physical structure, capable of using empirical data to optimize decisions and increase operational reliability.

The analysis of the presented architecture highlights the fact that predictive maintenance for complex manufacturing systems no longer represents just an isolated application of artificial intelligence, but an integrated ecosystem in which physical infrastructure, IoT technologies, distributed computing, cloud platforms and advanced analytics algorithms operate in a permanent relationship of interdependence. The value of this architecture derives from its ability to transform data generated by industrial processes into relevant information, and subsequently into operational knowledge and decisions that contribute to increasing the overall performance of the manufacturing system.

The information flow illustrated within the architecture demonstrates the transition from the traditional paradigm of reactive maintenance to an intelligent, anticipatory and adaptive model. The data collected at the equipment level is progressively processed through the IoT and Edge Computing levels, where it is filtered and contextualized, and then transferred to the cloud environment for complex analyses based on artificial intelligence and machine learning. In this way, the system acquires the ability to identify degradation trends, estimate the evolution of the

technical condition of assets and generate recommendations for interventions before critical defects occur.

From an industrial perspective, the implementation of such an architecture leads to reduced downtime, increased equipment availability, optimized maintenance costs and improved reliability of production processes. At the same time, the integration of predictive analytics with data-based decision-making mechanisms contributes to a more efficient use of material, energy and human resources, supporting current sustainability and industrial competitiveness objectives.

In conclusion, the analyzed architecture can be considered a representative model for future intelligent production systems, in which information flows, digital technologies and decision-making processes are integrated into a closed information loop, capable of ensuring continuous monitoring, prediction of system behavior and autonomous adaptation to operational conditions. Through this approach, predictive maintenance becomes not only a tool for reducing failures, but a strategic component of the digital transformation of modern industry.

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The Power of Color: Psychological and Marketing Effects of Color in Consumer Decision-Making

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Abstract: This literature review draws attention to the significance of color usage and demonstrates that color psychology is an indispensable component of the marketing communication toolkit. It examines the role of color in decision making through consumers' color associations and color symbolism. Color associations, color psychology, and color marketing are becoming increasingly relevant in the corporate sphere. Although the persuasive power of colors has been well documented, only a limited number of companies have incorporated these research findings into their practical operations to date. This paper was written to promote the conscious and strategic use of color. Its objective is to provide readers with a clear understanding of the psychological and physiological effects of colors, their significance, and the impact of their application in marketing communication. The findings of this research clearly indicate that linking color associations to products through packaging and corporate identity elements exerts a stimulating effect on purchase decisions. The emotional influence of colors is substantial, and as a result, consumer expectations and overall customer experience can be enhanced. Based on these conclusions, further research in the fields of color marketing and color psychology is recommended, particularly with regard to the color associations of Generation Z. As digital natives, members of this cohort encounter visually saturated environments on a daily basis; their responses to and associations with colors differ from the generalizable patterns. As the consumers of the future, understanding this generation's reactions to colors is essential for developing effective branding and packaging strategies.

Keywords: Color psychology, Color marketing, Color associations, Color symbolism, Consumer decision making, Consumer behaviour

1 Introduction

The use of color is an indispensable and central element of marketing communication. Purchasing decisions are significantly influenced by consumer

associations originating from a product's visual elements, and colors have a particularly strong impact on these associations [1]. Color psychology is therefore an area worthy of active research, as it can influence purchasing behavior through marketing tools, particularly with regard to impulse buying. Consumers form an opinion about a product in less than two minutes, and this decision is overwhelmingly influenced by colors [2].

The power of color marketing is becoming increasingly apparent to companies as well, yet many firms remain unaware of the power and significance of colors and do not incorporate the application of marketing psychology through colors into their practices. This decision is often not even a conscious one, as graphic designers and design professionals frequently rely on their intuition rather than basing color schemes on color psychology research [3]. The aim of this secondary research is to draw attention to the aforementioned problem and to encourage companies to consciously apply color psychology and color marketing.

2 The Effect of Colors

Colors have a special effect on people, even if we don't notice it in our everyday lives. Visual stimuli, especially colors, play a significant role in forming quick impressions and, in many cases, unconsciously influence consumers' attitudes and behavior [4]. We associate different moods, emotions, experiences, or knowledge with certain colors. When we recall these upon perceiving colors, we are making associations; we link our thoughts to shades and colors based on our memories.

Color association is a spontaneous and only very rarely conscious activity, yet it plays an important role in people's lives. Colors can be easily associated with objects, emotions, and events, but beyond these, we can also link colors to various sounds and melodies, types of materials, and scents or tastes. Although the meanings of colors may be culturally determined, certain associations appear in broadly similar ways across different societies [4]. Thus, the vast majority of people associate the same mental concepts with certain colors everywhere in the world. Examples include red for blood, blue for the sky, green for plants, or brown for the earth. This presumably developed during phylogenetic and ontogenetic evolution, based on experience [5].

Color associations generally direct people's thoughts toward the most common form in which a color is seen. Just because green is not only the color of nature but also the color of an object, people will not associate it with that object unless it has had a significant impact on them during their lives. We easily abstract from the colors of everyday objects when the selected colors have a much more significant and dominant presence in our environment [5]. We also associate various meanings linked to the meanings associated with individual colors with that particular color,

thus forming different chains of associations related to colors. These meanings are secondary, and fewer people perceive them as carrying that specific meaning, yet they still have a significant influence on our way of thinking.

Let us examine, for example, the more complex perceptions associated with the color blue. As I mentioned earlier, this color is almost universally linked to the sky. If we follow this line of thought further, we can also associate the sky with distance and inaccessibility, which we can then connect to God or the gods. A more complex association, therefore, is that blue is the color of the gods and of religion, which carries within it the meanings of purity and sublimity, thus becoming the color of knowledge and reliability as well. These chains of color associations, which apply to every color, play a very important role in the selection of colors. The practical application of knowledge about color associations is realized through the use of color codes and color symbols, which over time can become ingrained in people's minds and serve as carriers of the symbols' general meanings [5].

Color symbolism is a phenomenon that has developed over a long period of time, largely based on cultural conventions, and creates a connection between a specific concept and a particular color. This association is not random; it carries a deeper meaning shaped by the specific cultural and social context. Thus, colors form a kind of language through which emotions, meanings, and messages can be conveyed to individuals or groups who know and understand this color symbolism. Therefore, in addition to color associations, the culture of a given people also has a significant influence on color symbolism [6].

2.1 The Meaning of Colors

Different colors have different meanings that have evolved over the years. The general, international meanings of colors are an important consideration in color marketing. However, it is also important to take different cultures into account, as the meanings associated with colors can vary in different parts of the world. Yet most associations with colors have biological origins. These archetypal colors, which can be traced back to early humans, carry meanings rooted in instinct, as early humans recognized through colors which ones to avoid and which ones offered them safety. If we consider only the informative meaning of colors, subjective opinions can be ruled out; however, it is precisely because of this subjectivity that it is difficult to break colors down into unambiguous meanings, since everyone's own experiences influence their attitude toward colors [7].

Due to our biological makeup, humans tend to pay more attention to brighter colors, as plants and animals with these colors were often poisonous. Red, because of fire, conveys both warmth and danger, while green is the color of nature. Red fruits are much more popular than green ones, as we subconsciously associate the color with ripeness and sweetness, while green is a sign of unripeness [8].

Society has assigned meanings to numerous colors, which have retained these connotations to this day. These include, among others, pink and blue, which are the colors associated with girls and boys, especially in Western culture. This is already quite widespread, but there are still colors that carry different meanings across cultures, and in many cases, they convey completely opposite messages.

Red is also one of these colors; in China, red symbolizes good luck, whereas in Africa, it signifies mourning. In most countries, however, the color of mourning is black, while in East Asia, white carries the same meaning. In America, green is associated with money, since the dollar is green, but in Ireland it is the color of St. Patrick, the country's patron saint, while in Central European cultures, people tend to associate it with nature. Americans associate envy with money, so its color is also green, while in Central Europe this emotion is identified with the color yellow [1].

As I mentioned earlier, these days pink or red is the color for girls, and blue is for boys. However, this was not always the case. Based on Jeanne Maglaty's research, an article from 1918 (Earnshaw's Infants' Department; Earnshaw's Infants' Department) stated that pink, due to its vibrancy and because it carries more strength, is the color for boys, while blue is a much gentler and more delicate color, and thus belongs to girls [9]. This clearly shows that the meanings of colors can and do change over time. As a society's culture evolves, people's attitudes toward colors shift, and the meanings of colors change for them.

Color	General meanings	Culturally different meanings	Biological/archetypal origin
Red	Excitement, strength, activity, alertness, modernity	Good luck (China) Mourning (Africa) The color of girls (Western)	Fire: warmth and danger Ripe fruit: sweet Stimulating effect
Green	Life, nature, peace	Money (USA) Envy (USA) St. Patrick (Ireland) Nature (Central Europe)	Nature: harmony Unripe fruit
Yellow	Cheerfulness, optimism, friendliness	Envy (Central Europe)	Eye-catching
Blue	Trust, intelligence, expertise, logic	The color of boys (Western)	Used to be the color of girls: tenderness, delicacy

			Sky: stability, security
Pink	Openness, thoughtfulness, charm, femininity	The color of girls (Western)	Used to be the color of boys: strength (because it was vibrant)
Black	Elegance, wealth, opulence, dignity	Mourning (in general)	
White	Cleanliness, hygiene, light, peace	Mourning (East Asia)	

Table 1
Meaning of Colors (Source: Own elaboration)

The role of colors in marketing is of paramount importance, as they have a psychological impact on people's decisions. Certain colors influence consumers' minds in ways that either motivate or deter them in their purchasing decisions. Major companies are able to influence their customers simply by choosing the right colors [10].

The activating power of colors was already considered proven as early as the 1980s. In 1981, Küller published a book summarizing his experiments demonstrating the effects of colors. In 1976, for example, he conducted an experiment in which he placed six women and six men in color-rich and gray rooms for three hours each. Based on hourly measurements, it can be concluded that too much color can even negatively influence people's behavior, as the subjects, due to the chaotic visual impact and a lack of emotional control, behaved in a more withdrawn and reserved manner [11]. Therefore, it is advisable to use colors very carefully.

It is a proven fact that colors have a physical effect on the human eye: muscles contract and tense, and the pupil dilates or constricts when looking at certain colors. Psychological experiments have also demonstrated that colors can be used to facilitate powerful subconscious communication. If the visual presentation does not satisfy the consumer's aesthetic sensibilities—that is, if they encounter particularly disappointing color combinations—it can evoke negative emotions in them [12].

3 An overview of the practical application of colors

“The sight of certain colors makes us happier, more creative, hungrier, or more irritable, and this is nothing other than the emotional impact of colors.” [13]

Valdez and Mehrabian stated thirty years ago that colors have the power to influence emotions. Based on their 1994 research, it can be said that the brightness and

saturation of colors have a strong and predictable relationship with emotional reactions, meaning that certain colors can influence our emotions [14].

In addition to all this, colors also have an influence on human nature and behavior. In 2000, the color of street lighting in Glasgow was changed from warm yellow to blue to match the surrounding scenery. After this change, crime rates in these areas decreased. The same effect was observed in Japan when the lighting was switched to blue, and when the Keihin Electric Express Railway Company also switched its train lights to blue, the suicide rate decreased. This is attributed to the fact that people were much more cautious due to the unfamiliar lights. Moreover, since blue is the color of police lights, the illuminated area was perceived as a more strictly guarded zone, indicating that this association was made among residents.

In addition, the color blue can have a calming effect on people, since red and yellow—warmer colors—also signal danger. Blue light is also said to improve the condition of patients suffering from seasonal depression; a study on the effects of street lighting published in the journal *Trials* was medically reviewed by the Scientific Advisory Board in 2008. Of course, it would be reckless to claim that blue light alone cures people struggling with winter depression, but it is a fact that color therapy is used to treat seasonal affective disorder (SAD) [15].

In today's world, a surprising number of marketing companies seek to influence people through colors and color schemes, as colors can not only elicit emotional responses but also affect product perception, quality assessment, and purchasing decisions [4].

3.1 The appearance of colors in audiovisual content

Different shades and hues thus influence consumers' emotions, moods, and how they experience things, and this plays a major role in filmmaking as well. Lewis Bond's video, published on the Criswell YouTube channel in 2015, provides an excellent summary of the relationship between colors and films. This video served as the basis for numerous subsequent studies. I am drawing on the compilation by Mark Risk, which he created with the help of StudioBinder [16]. Risk's article demonstrates the effects that the color palettes of various films have on viewers.

Colors, as well as their brightness and shades, greatly determine a film's mood. Frequently used colors can trigger various emotional, psychological, and even physical responses in people. For example, the color red, if vivid enough, can raise blood pressure in certain scenes. These effects are often imperceptible to viewers, who are generally unaware of the psychological influence of colors [16].

Some films are covered with a distinctive color filter for nearly their entire runtime, thereby shaping the audience's perception of the film. If we take well-known films as an example, *The Matrix* (1999) wears a green "veil" throughout its runtime, so everything in the film is tinted with a slight greenish hue. I believe that this color

grading, in addition to making the film more mysterious and a bit more serious, is also intended to subtly implant digital elements—programming and computers—into people’s consciousness throughout the film, so that we feel as though we ourselves are part of a program.

In addition to *The Matrix*, color filtering throughout the entire film appears in other well-known movies as well. *The Twilight* (2008), popular among teenagers, also has a bluish tint, presumably intended to evoke a sense of coldness in the viewer, to showcase the characteristic weather of the city featured in the film, and to highlight the supernatural theme.

There are films that do not establish their overall mood by applying a single filter, but rather by excluding certain colors and working within a specific color scheme. An extreme example of such films is when the film itself is black-and-white and features only a single color, thereby evoking specific emotions in the viewer, which the chosen color further reinforces alongside the story. For example, in the 1924 film *Greed*, expressive elements within the film frames were hand-painted yellow. At the beginning of the film, only money was highlighted with the color, but as the frames progressed, yellow appeared more and more frequently, and by the end of the film, the entire image appeared in yellow. With this, the director sought to illustrate greed and how this trait consumes the protagonist, as the film’s title itself signifies: greed [17].

It may also be the case that in a given film, one color takes on a more significant role and meaning than the others, but every color appears on screen. If we focus on red, which is one of the most defining primary colors, it can mean different things in different contexts. Red is generally associated with the strongest human emotions, such as love, desire, or anger. Its appearance can represent warmth, passion, and sexuality, but it often carries negative connotations, such as violence, danger, or aggression [18]. In the film *The Sixth Sense* (1999), the color red symbolizes fear, dread, and foreboding, while the film *Pleasantville* (1998) uses red to express hope, love, and sensuality. Because the color red evokes intense emotions in the viewer, it should be incorporated into a film’s color palette with care and deliberation [16].

All in all, it can be said that when we watch a story on screen, colors trigger psychological reactions in us. They can direct our attention to important details, set the mood of the film, depict certain characteristics of the characters, and also represent changes or continuity within the story [16].

3.2 The Effect of Color Use on Purchasing Behavior

Colors are playing an increasingly important role in people’s lives, so marketing must pay special attention to them. Eighty percent of impulse purchases are influenced by colors. This means that a consumer is more likely to purchase certain products if they like their colors and find them appealing. Different colors evoke

different reactions in consumers, so companies looking to break into the market must choose them wisely [19].

3.2.1 Packaging

We might decide not to buy a product that's perfect for us in a store because the colors of the packaging don't accurately reflect the product's nature. For some manufacturers, misleading consumers with colors might attract customers, but at the same time, it can drive potential buyers away from the products that are best suited for them. Every shopper automatically forms a mental image of the product or service as soon as they see the packaging or advertisement. Colors and color combinations play a major role in this, as different emotions are associated with each color, most of which are subjective and easily generalized.

When shopping, our environment subconsciously influences our psychological reactions: the packaging of products, advertisements, and the colors of various lights. A great deal of research has been conducted on this topic worldwide, but I am examining the work of a Hungarian researcher. Füredi wrote in an article that, on average, 93% of our purchases depend on how the product looks, and 85% on the color of its packaging. It takes just a minute and a half to form an opinion about a store or a product, which influences our attitude toward shopping. Color psychology plays a very important role in our daily lives, even if we don't realize it [2].

3.2.2 Branding

Beyond packaging, colors and shades play a crucial role in many areas. The color of the logo, the colors used on business cards, and the consistency of the website's color scheme are all essential to a business owner's success. In addition, the colors used by social media professionals, the color palette of emails and company presentations, as well as the colors of flyers, posters, and online ads – that is, the colors used in the company's brand identity – all contribute to the perception of the product or service. Based on the colors displayed, customers categorize products; therefore, if these are not all in harmony, potential consumers cannot form a sophisticated mental image of the company [1].

As noted in a 2012 issue of the *Journal of the Academy of Marketing Science*, colors and shades play a significant role in brand building. Different colors convey different meanings to consumers and potential customers, as demonstrated by the research of Lauren Labrecque and George Milne [20]. When building a brand, it is important to ensure that its colors convey sincerity, for which shades of white, yellow, and pink are recommended. White is the color of purity, hygiene, brightness, peace, and, in some cases, happiness; people associate yellow with cheerfulness, honesty, optimism, and friendship; while pink is the color of openness, honesty, care, warmth, and tenderness. According to the results of a study

featured in the journal, conducted by Labrecque and Milne with high school students, yellow only partially conveys sincerity to people when used in logos and brands, whereas white and pink confirmed the hypothesis.

Shades of red, orange, and yellow can be used to convey a brand's excitement and uniqueness. Red is the color most closely associated with excitement, but it also signifies strength, activity, alertness, and has a stimulating effect, as well as conveying modernity. Orange also conveys excitement, but less intensely than red. Its use results in a lively, energetic appearance and symbolizes openness and community. Research supported the hypothesis regarding the color red, but the association that orange is an exciting color is only partially true, and the color yellow did not yield any positive results at all.

Expertise and intelligence can be represented by shades of blue and brown when defining a brand's color scheme. Blue represents trust, communication, intelligence, expertise, and logic; it is considered one of the safest colors on the color spectrum. Brown, on the other hand, conveys seriousness, reliability, and support. According to the survey, high school students did not associate brown with expertise, whereas blue corresponded to the hypothesis.

We can convey sophistication and refinement through the use of black, purple, and perhaps pink. Black conveys taste and charm and plays an important role in the fashion world: it is an expression of status, elegance, wealth, and dignity—just think of black suits, evening gowns, or limousines, and the color black is sure to come to mind for most of us. In addition, purple is a symbol of luxury, authenticity, and quality, likely due to the role the color has played throughout history, as burgundy and purple were both considered royal colors. Pink is also considered a sophisticated, feminine, and charming color. Among the study participants, black, purple, and pink did indeed convey an impression of sophistication.

The colors brown and green can be used to convey vitality and a strong, rugged brand image. Brown is associated with vitality because of its connotations of seriousness, nature, and the earth; in addition, we can also associate reliability, protection, and support with brown. Green clearly signifies the color of nature; thus, as the color of life, it exudes calm and represents a connection to the outside world. Research also confirms that people associate vitality with brown, but not at all with green [20].

This survey is a good example of how color associations do not necessarily mean the same thing to different age groups. The authors of the journal drew on sources dating back as far as 1942, with most of their sources originating from before the turn of the millennium. Of course, these studies should not be disregarded simply because a different result emerged among high school students in 2011. Rather, they should be viewed as evidence that colors likely affect different generations in different ways.

3.2.3 Communication

Good advertising appeals to emotions, just like colors do, so it's no surprise that the power of colors is often used in marketing as well. Depending on who our target audience is, we can use different colors. For example, when looking at gender preferences, women tend to prefer purple, green, and blue, while men prefer blue, green, and black. There are certain colors that are not recommended for use in advertisements because neither gender particularly likes them. Examples of such colors include brown and orange.

It's important to remember that marketing isn't just about commercials or posters. When designing websites, banners, and similar online ads, it's also worth considering that certain colors can lead to higher conversion rates. These colors include green, yellow, red, and orange, which, although not particularly favored by either gender, still achieve good results in terms of engagement [13].

Thanks to the lighter color scheme, visitors will feel comfortable on our site, which may lead them to make more purchases, but of course, there are downsides to this as well. If we want to publish more information on the site, the lack of adequate contrast will prevent us from conveying that valuable information to visitors; they won't notice it, won't be able to process it as easily, or simply won't consider it important [13].

Looking at the specific use of colors, red is a highly attention-grabbing shade; due to its blood pressure-raising and appetite-stimulating effects, it is used by numerous fast-food chains, food brands, and even retail chains. Examples include—among many others, of course—Coca-Cola, Burger King, KFC, Tesco, Spar, and Auchan [19]. Blue is one of the colors most closely associated with nature, due to the blue sky, and it can also increase work efficiency. It is the color of wisdom and trust, so many electronics companies and payment processing firms prefer to use this color, such as Samsung, PayPal, Visa, and Dell [21]. The third primary color is yellow, alongside red and blue. We associate it with daytime, so it radiates cheerfulness and optimism. It is the most eye-catching color and is excellent at grabbing shoppers' attention, making it very popular, especially when the goal is to encourage impulse buying. Among brands that use this friendly color, the most famous is undoubtedly McDonald's, but Ferrari and Nikon also fall into this category [19].

It is important to choose colors carefully in marketing, as different color combinations have different effects. There is a great deal that could be written on this topic, as we have an almost infinite number of different shades of colors at our disposal, and with the help of digital technology, we can even distinguish them using numbers, a so-called HEX code [22].

Sticking to the primary colors—that is, examining only blue, yellow, and red—I'd like to highlight a striking example of color pairing. When using a single color, its fundamental meaning comes to the fore; however, colors should be paired in such a way that the final result is neither too cool nor too warm in tone, as these can be

misleading and may not necessarily convey the intended message. It is therefore not surprising that blue is the most commonly used color in logos, and it is often paired with, for example, yellow or a shade of red [23]. A perfect example of this is the Scandinavian home furnishings brand, Ikea, whose blue-and-yellow logo is internationally recognized.

However, if we use very saturated shades of red and blue without pairing them with any other color—such as white—we end up with an overly intense, jarring combination that can be irritating to consumers [24]. This is precisely why Pepsi uses these colors in combination with white; the brand has grown into a world-famous, recognizable brand with vibrant yet visually pleasing design elements.

Blue is a very popular color in company logos. According to Interbrand research, more than a quarter of the world's 100 most influential brands use this color in their logos. In fact, 5 of the world's 10 largest and most popular brands have blue logos [25].

When all three primary colors are used in a single logo, they reflect playfulness, youthfulness, and childlike qualities. Burger King used these colors from 2000 all the way through 2021, until their rebranding, when the color blue was removed from the logo. But these colors are also found in the logo of the famous Pixar animated series Toy Story, which is aimed at children and features toys in the lead roles [23].

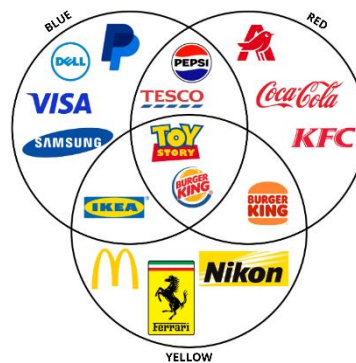


Figure 1

Venn diagram of logos using primary colors (Source: Own elaboration)

In short, while a brand's uniqueness, visual appeal, and aesthetics are important, it is essential to pay close attention to the careful selection of colors. A potential customer's first impression of a brand comes from its logo, so the logo's color is of paramount importance to a company's success.

Conclusions

This secondary research focuses on the significance of colors and their impact on consumers' emotions and purchasing decisions. The use of color by brands on websites or packaging can influence consumer behavior and may encourage or discourage potential customers from purchasing certain products or services.

To gain a thorough understanding of the topic, the research examines color marketing, specifically color symbolism and the meaning of colors, as well as the use of different colors in a company's brand identity. In addition, it introduces the reader to the effects, chains, and formation of color associations, and also addresses color psychology and color marketing as it influences consumer emotions.

The influential and motivational effects of colors are well-established; they are considered central elements of consumer decision-making. Subconscious needs can be shaped through visual presentation, making their conscious and ethical application essential from a corporate perspective.

This research does not aim to find solutions to the problems that arise. Its purpose is to draw the attention of future researchers to the study of the deceptive effects of colors. Through secondary research, the power of colors in marketing can be understood, and it demonstrates that this area of sensory marketing should not be underestimated.

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Life-Cycle Cost Analysis And Health Technology Management Of Diagnostic Medical Equipment In Ugandan Public Hospitals: Financial Sustainability Challenges And Strategic Opportunities For Improvement.

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Abstract: Diagnostic medical equipment plays a crucial role in the modern healthcare system. They aid in accurate disease diagnosis and guide critical clinical decisions. However, many Low and Middle-Income Countries (LMICs) face persistent challenges in maintaining their functionality and sustainability. The reason is because they are often designed for countries with efficient healthcare systems and adequate resources. This article examines the life-cycle costs and financial sustainability of diagnostic medical equipment in Ugandan public hospitals. A literature-based research approach was employed basing on secondary data from World Health Organization reports, Ministry of Health reports and peer-reviewed literature articles. These were complemented by expert insights from biomedical engineers in practice. A substantial proportion of diagnostic equipment in many public hospitals experience prolonged downtime due to reactive maintenance practices, fragmented procurement systems and insufficient funds allocations for operational costs. Infrastructural challenges such as unreliable electricity supply and poor facility design also negatively impact equipment performance. The article emphasizes the importance of integrating life-cycle cost analysis into the procurement and asset management frameworks. Strengthening healthcare Technology Management systems through preventive maintenance approach, digital equipment registries, workforce development and improved procurement coordination can significantly enhance the sustainability of medical equipment. Institutionalizing these strategies will be critical in improving the diagnostic capacity and ensuring long-term resilience of Uganda's public healthcare system.

Keywords: Life-Cycle Cost Analysis, Health Technology Management, Medical device, Diagnostic medical equipment, Public hospitals, Healthcare system

1 Introduction

The third Sustainable Development Goal (SDG) pertains to Universal Health Coverage (UHC) and the provision of quality essential health services. One of the most important factors in determining a health facility's efficiency is the patient's length of stay. In an attempt to operationalize and realize effective healthcare service to its citizens, the government of Uganda, through the Ministry of Health emphasizes the importance of having properly functional medical equipment in all the public health facilities [1]. In order to provide quality healthcare to the local population in Uganda, the government recently created more district health facilities and regional referral hospitals established in every region [2]. Public hospitals account for over 40% of the entire health expenditure in several Sub-Saharan African countries, and Uganda is no exception [3], [4].

The Ugandan public health care system, however, continues to face significant challenges in providing timely healthcare services to the general public. Some of the contributing factors to this are the malfunctioning referral systems, operative capacity restrained by inadequate infrastructure and overwhelmed by emergency volume, critical workforce shortages, and prolonged downtime of medical equipment in the hospitals [5]. In many cases, the concerned stakeholders overlook the importance of timely maintenance of critical diagnostic equipment. The mentality that equipment is only serviced or repaired once it has completely broken down is widespread in low-resource settings. To ensure effective management of failures and associated costs in medical equipment procurement, maintenance, and disposal, it's important to develop a reliable approach for anticipating failures.

Furthermore, Uganda also experiences a notable deficit in medical equipment relative to World Health Organization guidelines, alongside an uneven distribution of the available equipment, especially in the area of diagnostic imaging [6]. In higher-tier facilities, modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) are available, though their numbers remain limited. Uncertainties continue to be induced by the ongoing healthcare reform and the year-on-year increase in general healthcare expenditures. The expansion of patients' medical needs and healthcare providers' concern to extend the life of assets while minimizing operational costs for medical equipment remains challenging to address.

Ensuring the availability, performance, and safety of medical equipment is crucial for providing quality, reliable healthcare services in modern systems. Currently, Uganda lacks a national reporting database for medical devices in all the public

hospitals. The structure of the biomedical engineers and technicians is not well-balanced. A ratio of four biomedical engineers to one biomedical technician in the referral hospitals is not a realistic and functional structure for efficient equipment management. Many healthcare facilities often manage medical device procurement, maintenance, compliance, decommissioning, and financial planning autonomously. There is very little consultation between top management, the procurement department, the engineering department, and the actual equipment users. Managing these components independently, however, is insufficient, as new factors impact medical efficiency and safety [7]. This article examines the financial and social implications of poor medical equipment life-cycle management in Ugandan public hospitals, with particular focus on frequent breakdowns, high repair costs, and reliance on donations. It shows how inadequate equipment management impacts not only the financial stability of healthcare institutions but also the quality of care and the social well-being of patient populations. Additionally, it aims to identify and evaluate existing frameworks that could promote sustainable and effective use of medical equipment in low-resource healthcare systems. The article further examines how life-cycle cost analysis influences budgeting and equipment purchasing decisions. Examining these factors demonstrates how crucial it is to incorporate thorough cost analysis into healthcare management procedures to maximize equipment use, improve resource allocation, and strengthen financial sustainability in Uganda's public health sector.

2 Literature review

The World Health Organization (WHO), in agreement with the International Medical Devices Regulatory Forum (IMDRF), defines a medical device as any article, instrument, apparatus, or machine that is used in the prevention, diagnosis or treatment of illness or disease, or for detecting, measuring, restoring, correcting or modifying the structure or function of the body for some health purpose. Medical equipment, on the other hand, is defined as medical devices requiring calibration, maintenance, repair, user training, and decommissioning, activities usually managed by clinical or biomedical engineers in the hospital.

Healthcare is a term used to describe the diagnosis, treatment and prevention of illness. It is frequently described as consisting of three sectors, primary, secondary and tertiary care [8]. Families and social networks provide informal healthcare in their homes and communities. Secondary care describes care provided by medical specialists and usually delivered within a hospital setting. Tertiary care is specialist consultative care. It usually involves admission to a hospital that provides a high level of specialist care in the management of, say, cancer or the provision of specialist surgery such as cardiac surgery or neurosurgery [9]. However, with clinical and technological developments occurring within the context of evolving

social, population, and economic environments, the distinctions between primary, secondary, and tertiary care continue to blur. Nonetheless, the distinctions between these levels of care are useful when considering the spectrum of healthcare provision. Hospital efficiency is vital for the overall health system, as they use significant resources.

Figure 1 illustrates these healthcare sectors, which summarize how societies structure the healthcare system optimally to meet the need for diagnosis, treatment, and prevention of illness. The arrows indicate the referral pathways. These are bidirectional, as the objective is always to improve the health of the individual, no matter where they are in the healthcare system, and in doing so, to move the individual towards independent living in the community.

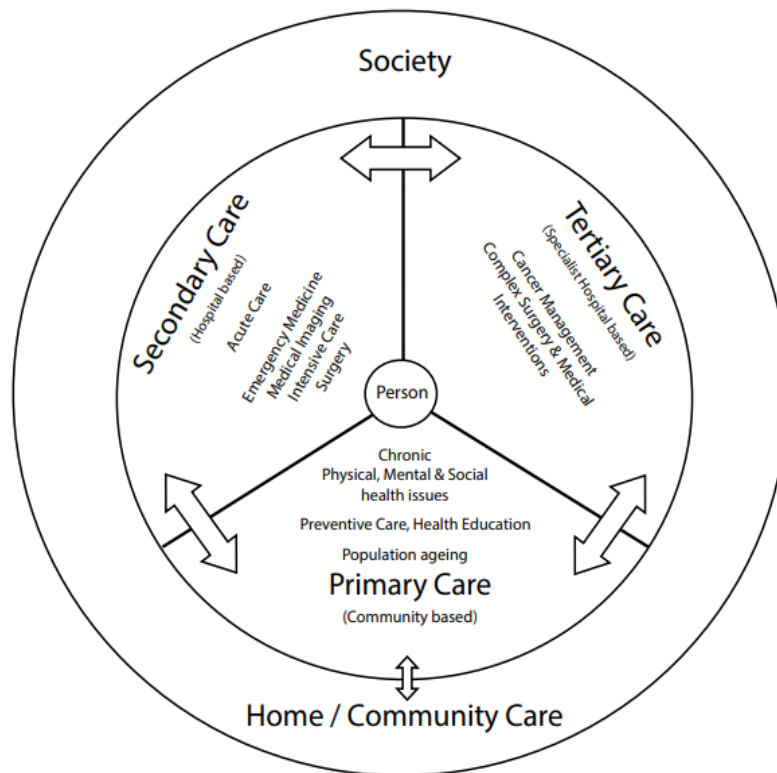


Figure 1
Showing the conceptual model of integrated healthcare delivery

An effective healthcare system heavily depends on the functionality of medical equipment. The life cycle of these medical equipment can simply be thought of as the different stages involved from the time of design conception to its end of use/decommissioning [10]. It varies globally based on infrastructure, resource

when selecting medical devices. These can include technical specifications and population priorities and needs. In practice, it involves assessing whether a device's functionalities correspond with medical procedures and the local disease burdens. After identifying the requirements, the technical team should then verify the device's performance parameters (accuracy, capacity, and software features) and ensure regulatory authorities approve it and meets quality standards. Compliance with a quality management system (QMS) standard, such as ISO 13485, indicates a manufacturer's stringent practices for ensuring device safety and effectiveness [13], [14]. Another very critical aspect of the selection process is assessment of the supplier's credibility and of the support it will provide. This is extremely important that during the equipment's term of use, it will need frequent maintenance. The earlier this is put into consideration and planned for, the better the financial allocation.

Budgeting and cost are key factors in procurement choices. Decision makers should include in the purchase price to compute the total cost of ownership for a product. This covers installation, user training, planned and preventive maintenance, consumables, and energy expenses to operate. A device that is relatively cheap to acquire yet requires highly expensive consumable supplies or has a significant downtime may not be cost-effective in the long run. Procurement committees evaluate devices based on their therapeutic advantages, long-term operational costs, and compatibility with other systems. Compatibility with other equipment and information technology (IT) systems allows for seamless integration of new digital devices. Consideration of compatible devices prevent hidden expenses and technical issues [15].

Proper installation involves more than just plugging in a machine. It also includes site preparation, device performance verification, and user training to ensure safety. The first step is often ensuring that the location at which the device will be used meets all the site requirements for power supply and ventilation among others. The installation is usually done by technicians or engineers with support from the supplier's technical team if the team on ground is not very well conversant with the equipment to ensure flawless installation. After assembly, initial tests or first inspections are carried out. It involves testing and validating a device before it is used in the clinical practice. Its objective is to ensure that the device conforms with the authorized design and satisfies all defined criteria made at the needs assessment. Biomedical engineers or skilled technicians often conduct performance and safety inspections following international standards or manufacturer specifications. This phase checks that the device is functioning properly and safely after installation. Thereafter, the users of the equipment are taken through training in order to be able to use the equipment properly for the purposes it is intended for. As the equipment is used, the clinical or biomedical engineers ought to continue undertaking performance monitoring tracking for optimization, routine maintenance for prolonged life span. Medical devices, like any complex equipment, degrade or require re-calibration over time [16]. Without proper upkeep, they may fail

unexpectedly or give inaccurate results, which could directly impact patient outcomes. Replacement of worn-out parts and update of software are done on the equipment depending on the need. This is a very crucial stage in the life cycle management because how long the equipment remains in good operational status relies entirely on how it is maintained at this stage.

Medical devices have a limited lifespan owing to age, wear and tear, or technical advancements. Decommissioning and disposal involve safe removal from the healthcare facility and properly disposing of it through recycling, donation, or reuse. This stage must be appropriately managed to guarantee health, environmental safety, and legal compliance. The WHO guidance emphasizes that medical equipment should be decommissioned in a structured way, with clear reasons and methods. In practice, health-care facilities should assess when a device must be taken out of use, how to do so safely and how to dispose of the device. In conjunction with reprocessing and reusable equipment, improvements in recycling are also essential to increase sustainability in medical equipment life cycles [17]. There is an absence of a widespread, effective medical recycling system because of a lack of knowledge. For example, over-classification of hazardous medical waste in hospitals results in missing recycling or reprocessing possibilities. Medical plastics that may be recycled are placed in red biohazard trash bags.

3 Methodology

The article adopted a literature-based research approach, relying on secondary data from World Health Organization and Ministry of Health reports, as well as peer-reviewed literature. These were complemented by expert insights from biomedical engineers in practice. The major emphasis was on the sequential analysis of events and factors affecting the life-cycle management of diagnostic medical equipment in Ugandan public hospitals. This approach enabled a thorough tracing of how procurement, maintenance, operation and financial sustainability challenges have evolved over time. The use of this study design also allowed for an understanding of the relationship between policy changes, technological adoption and financial outcomes within the healthcare sector.

The study area focused on public hospitals in Uganda, mostly the national and regional referral hospitals where critical diagnostic medical equipment such as X-ray machines, CT and MRI scanners and laboratory analyzers are highly concentrated. The study scope covered equipment acquisition, procurement processes, maintenance practices and associated costs, human resource capacity and financial decisions that affect sustainability and planning. The choice of this focus was based on the critical role that these hospitals play in Uganda's healthcare delivery and their high dependence on government funding and donor-supported technologies/medical equipment.

The article employed a combination of secondary data review and key information insights. Documents and reports reviewed included the Ministry of health reports, WHO guidelines, National Medical Stores (NMS) procurement reports. Scholarly peer-reviewed articles were also searched for and read. These publications were on healthcare technology management and life-cycle cost analysis. Furthermore, policy and institutional analysis examined the Public Procurement and Disposal of Public Assets (PPDA) Act and several frameworks governing equipment management. All the data sources were carefully assessed for relevance and credibility to ensure valid findings. Expert consultations were drawn from biomedical engineers and hospital administrators to contextualize observed challenges in public hospitals.

For ethical considerations, no personal identifiers were used since the study relied primarily on secondary data and expert consultation. Institutional documents and publications from Web of Science and Google Scholar were cited according to academic standards. Expert opinions were anonymized to maintain confidentiality and respect organizational policies. However, the greatest limitation faced was restricted access to up-to-date maintenance cost data and inconsistencies in hospital reporting systems. Additionally, the reliance on secondary information limited the extent of quantitative verification. To overcome this, cross-referencing multiple credible data sources and validation of findings with expert perspectives were considered.

4 Results

4.1 Current state of diagnostic medical equipment in Ugandan public hospitals

Uganda's public health system operates within a decentralized framework that includes national referral hospitals (NRH), regional referral hospitals (RRH), general hospitals, and lower-level health facilities [18]. Each level is expected to provide progressively advanced diagnostic services. The study revealed that diagnostic medical equipment in Ugandan public hospitals is characterized by partial availability and limited functionality. A 2022 assessment by the Ministry of Health reported that while over 70% of regional hospitals had functioning ultrasound and X-ray units, only two public facilities, that is Mulago NRH and Mbarara RRH possessed operational MRI scanners. Most advanced diagnostic imaging equipment remains concentrated in urban centers, with the private sector and faith-based hospitals contributing significantly to the availability of CT and MRI services. A 2020 Hospital Infrastructure Insight Uganda report indicated that there were about 150 hospitals (both private and public) in the country, with about

38 providing tertiary healthcare. However, functional disparities persist within basic diagnostics. As a result, equipment downtime is frequent and directly affects service delivery, increasing patient waiting times. Many district hospitals operate outdated analog X-ray systems with limited image quality. A significant proportion of laboratory diagnostic equipment, such as chemistry and hematology analyzers, is donor-procured, leading to a mix of brands and models that complicates maintenance and standardization. The overall picture is one of partial coverage but uneven functionality, where the presence of equipment does not necessarily equate to service readiness [19].

4.1.1 Procurement Processes and Funding Mechanisms

The procurement of medical equipment in Uganda is guided by the Public Procurement and Disposal of Public Assets Act (PPDA) and sector-specific guidelines issued by the Ministry of Health. The key procurement agencies are National Medical Stores (NMS) and Joint Medical Stores (JMS) for public facilities and private not-for-profit facilities, respectively. While the regulatory framework emphasizes transparency and competition, the practical implementation of procurement for diagnostic equipment remains fragmented.

Funding sources include the central government, development partners, and donor-supported projects, with additional input from district and hospital budgets. Donor-funded procurements, while vital, often occur outside standardized national planning, leading to mismatched equipment and duplication across facilities. Moreover, procurement processes frequently prioritize initial acquisition cost over long-term sustainability, with limited attention given to life-cycle costs, spare parts, and maintenance contracts. The Ministry of Health has made progress by introducing the National Medical Equipment Guidelines (2024), which recommend the inclusion of Total Cost of Ownership (TCO) analysis and post-installation support in all procurement activities. However, enforcement remains a big challenge across all hospital levels.

4.1.2 Maintenance, Usage, and Operational Challenges

One of the most persistent issues in Uganda's diagnostic infrastructure is the high rate of non-functional equipment. Research shows that between 30–40% of medical devices in public facilities may be out of service at any given time, largely due to a lack of spare parts, consumables, or technical expertise [19]. This results in equipment downtime that compromises service delivery and patient safety. Maintenance of diagnostic equipment is largely reactive rather than preventive. Most facilities lack scheduled maintenance plans or service contracts with suppliers. Regional biomedical workshops established in Gulu, Mbale, and Mbarara have helped improve repairs, but their reach remains limited. The absence of ring-fenced maintenance budgets means that equipment servicing competes with other pressing expenditure needs.

Another major challenge is the inconsistent supply of consumables. Radiology units frequently experience shortages of films, reagents, and printer cartridges, rendering functional machines unusable. In laboratory departments, stockouts of quality-control and calibration reagents disrupt analyzer operations and compromise data accuracy. Additionally, donated equipment, though valuable often arrives without adequate documentation, user manuals, or compatibility with local utilities. Some devices require stable electricity or specialized maintenance support, which is unavailable in rural hospitals. Without standardized procurement and user training, such donations sometimes become non-functional soon after installation. Operational inefficiencies also stem from limited user training. Nurses and clinicians often lack familiarity with device care, leading to misuse or neglect. For example, poor handling of ultrasound probes and inadequate cleaning practices reduce device lifespan and diagnostic accuracy.

4.1.3 Infrastructure and Human Resource Considerations

The availability of diagnostic equipment alone is insufficient without the infrastructure and human resources necessary for operation. Many district and regional hospitals in Uganda lack reliable power supply, favorable environmental conditions and appropriate space requirements for advanced medical diagnostic equipment. Frequent power fluctuations not only interrupt diagnostic procedures but also damage sensitive electronics. In some hospitals, radiology departments are housed in improvised spaces without adequate shielding, ventilation, or patient flow design, compromising safety and efficiency. Human resources present an equally critical constraint. The biomedical engineering workforce remains small relative to the number of facilities requiring support. As of 2023, Uganda had fewer than 300 well trained and qualified biomedical engineers and technicians serving over 6,000 health facilities. This shortage leads to long repair turnaround times and dependence on external contractors.

4.2 Opportunities and strategies for improved technology management in the healthcare sector

The findings of this study underscore the critical importance of adopting a life cycle cost (LCC) approach in managing diagnostic medical equipment within low-resource healthcare systems. The high rate of non-functional equipment reflects a systemic failure to integrate procurement, maintenance and overall financial planning into a unified framework. Procurement sets the foundation for all subsequent stages of equipment management. In Uganda, fragmented procurement processes and limited coordination between users, technical teams, and suppliers have often led to acquisition of unsuitable or poorly supported technologies. A shift towards evidence-based and standardized procurement is essential. Facilities should base purchasing decisions on verified user requirements, life-cycle costs, and

compatibility with existing infrastructure. Introducing a Total Cost of Ownership (TCO) framework will ensure that budgeting covers not only acquisition but also installation, training, spare parts, and disposal.

4.2.1 Implementing preventive maintenance and life-cycle planning

Historically, equipment maintenance in Uganda has relied on reactive repair, addressing breakdowns only after they occur. This approach is costly and leads to prolonged downtime. A preventive maintenance culture should therefore be institutionalized within all healthcare levels. A structured maintenance framework can be organized in four categories. At the user-level care, clinical staff perform basic cleaning and operational checks. In-house maintenance should be conducted by facility biomedical technicians. Regional workshop support offering calibration and complex repairs and specialized or manufacturer service for high-end technologies. The MoH's regional biomedical workshops serve as key maintenance hubs. However, to sustain their impact, a dedicated maintenance budget line must be incorporated into annual health facility plans. Routine inspections, asset tagging, and monthly functionality reports should be mandatory. Developing equipment life-cycle plans including expected lifespan, replacement intervals, and decommissioning guidelines will also enhance long-term planning.

4.2.2 A tiered capacity building approach of training for biomedical personnel

Human resource capacity remains one of the most pressing challenges in Uganda's HTM system. Many facilities lack adequately trained biomedical engineers, and users often have limited understanding of equipment operation. A tiered capacity-building approach can address this challenge. At the basic level, nurses and clinicians should be trained on proper handling and routine care of devices. At the technical level, biomedical technicians require continuous professional development in maintenance, calibration, and troubleshooting. Partnerships between the MoH, training institutions, and the private sector actors can provide structured mentorship and certification programs.

Several institutions of higher education have made progress in training biomedical engineers and technologists. However, more emphasis is needed on practical exposure and regional mentorship, ensuring that skills gained are applicable within the local health system. Establishing a national registry of all the biomedical professionals in the country would also improve deployment, monitoring, and professional recognition. Blended learning combining short face-to-face sessions with digital learning modules offers a cost-effective method for continuous training. E-learning programs for medical engineers provided by the manufacturers of medical devices shows that hybrid approaches enhance retention and reduce travel costs yet keep the engineers with most up-to-date developments for their daily troubleshooting and repair works.

4.2.3 Leveraging technology and innovation

Modern innovations provide practical opportunities for transforming health technology management (HTM), a critical yet an underdeveloped component of the healthcare system in Uganda. Efficient management of medical equipment directly influences service quality, patient safety, and financial sustainability. Remote monitoring systems, supported by Internet-of-Things (IoT) technologies, enable real-time tracking of critical equipment. Data from these systems can alert technicians to early faults, reducing downtime [20]. Similarly, mobile maintenance applications could support biomedical teams in logging repair tickets, accessing spare-parts inventories, and generating maintenance reports from the field. Another promising area is equipment reconditioning and local refurbishment. Establishing refurbishment centers for common devices would reduce costs and enhance sustainability thus creating opportunities.

In order to achieve optimal outcomes in healthcare facilities, a holistic strategy beyond controlling individual procedures is necessary to integrate modern technology. The transition to data-based, automated, environmentally responsible practices in medical device inventory and maintenance management is no longer optional but is essential for ensuring high-quality, sustainable, future-ready healthcare systems. The scope of HTM thus extends beyond simple asset management, but rather to a comprehensive strategy that integrates technology, policy and sustainability to improve health-care efficiency, patient safety and long-term system resilience. Understanding the medical device life cycle is fundamental to HTM, as it demonstrates the importance of an interconnected system in which procurement, maintenance, regulatory compliance, financial planning and sustainability are integrated rather than managed independently. Health-care technology is only as effective as its management [21]. Below is an illustration of the interconnection of the different components could be integrated into one solid framework, the HTM system.

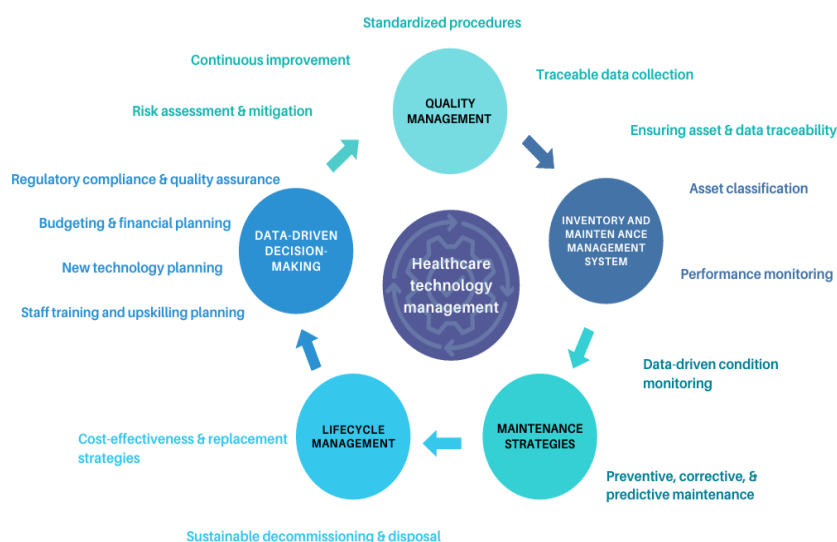


Figure 3

Showing the HTM model for effective equipment management.

Source: Inventory and maintenance management information system for medical devices WHO: Medical device technical series

Modifications to some of the component actors or interactions from this technological process, as well as the incorporation of other interactions or actors, might be carried out based on the knowledge of the improvement activities [22]. Effective technology management requires an enabling policy and financing environment. The establishment of a national HTM policy framework that clearly defines roles, standards, and reporting requirements would be a game-changer.

4.2.4 Policy and partnership recommendations

The promotion of public-private partnerships (PPPs) for training, maintenance, and spare parts supply is highly recommended. Encouragement and support of local innovation and manufacturing, particularly for low-complexity equipment, consumables, and accessories will play a big role. Lastly, the integration of equipment data into a national health information system to improve transparency and planning. Sustaining and scaling these partnerships will be vital for achieving national coverage. Additionally, developing equipment refurbishment centers could extend the lifespan of diagnostic devices and reduce dependence on imported machines. Private-sector partners such as Crown Healthcare (U) Ltd have demonstrated that local reconditioning of laboratory devices is feasible and cost-effective. Expanding these models under public-private partnerships would not only enhance equipment availability but also build local technical capacity.

Financial sustainability emerges as the central challenge in all the above. This is very significant in public hospitals that rely heavily on constrained government budget and donor funding. Even when capital investments are made, recurrent costs of maintenance, consumables, power, and human resource expense often outstrip available budgets. Public hospitals operate under constrained annual budgets. Capital acquisitions are frequently supported by one-off donor funding or special projects, but recurrent budgets rarely account fully for maintenance or consumables. The problem is that facilities receive equipment without reliable financial plans for its upkeep and operation. Central allocations, district budgets and donor projects coexist without harmonized planning. To address some of these burdens, there is an urgent need to allocate resources towards the proper maintenance of equipment. The disconnect between capital investment and recurrent funding creates a cycle in which equipment is procured but not operated sustainably.

Integrating diagnostic planning into broader health infrastructure investments such as power stabilization, digital record systems, and telemedicine will create a more resilient and interconnected diagnostic ecosystem. Uganda's public health system has made meaningful progress in expanding diagnostic capacity, yet significant challenges persist in ensuring equitable access to, functionality of, and sustainability of diagnostic equipment. The country's diagnostic landscape is characterized by an uneven distribution of advanced technologies, fragmented procurement, inadequate maintenance, and a shortage of skilled personnel. Addressing these challenges requires a holistic approach that links procurement reforms, maintenance planning, infrastructure investment, and human resource development. Policies should prioritize preventive maintenance, enforce total-cost-of-ownership frameworks in procurement, and ensure sustainable funding for biomedical engineering functions.

5 Discussion

The findings suggest that the challenge of diagnostic medical equipment in Ugandan public hospitals is not simply that machines are unavailable. A more serious problem is that many existing machines are not consistently functional. Some hospitals have basic equipment such as X-ray and ultrasound units, but these devices may be old, poorly maintained, or unusable due to missing consumables, spare parts, unreliable power supplies, or limited technical support. This means that equipment listed in a hospital inventory may not reflect the real diagnostic capacity of that facility. The uneven distribution of advanced technologies also remains a major concern. Equipment such as MRI and CT scanners is still concentrated mainly in urban and referral hospitals, leaving many district and rural patients with limited access to advanced diagnostic services. For these patients, diagnosis may involve long travel distances, additional costs, or referral to already congested higher-level

hospitals. This shows that weak equipment management is not only a technical issue; it directly affects equity, affordability, and timely patient care.

Procurement and maintenance practices appear to be key contributors to the problem. Equipment is sometimes purchased or donated without enough planning for installation, user training, service contracts, consumables, spare parts, and future replacement. In addition, maintenance in many facilities remains reactive, with repairs only carried out after breakdowns occur. This increases downtime and makes service delivery unreliable. A preventive maintenance system, supported by proper records and dedicated budgets, would therefore be more suitable for sustaining diagnostic services. Human resource and infrastructure gaps also limit equipment performance. The shortage of biomedical engineers and technicians means that faults may take long to be addressed, while unstable electricity, inadequate space, poor ventilation, and weak safety provisions can shorten the lifespan of sensitive diagnostic equipment. These challenges show that medical equipment planning should not be separated from hospital infrastructure development and workforce planning.

A stronger Health Technology Management system in Uganda will be of great impact. Diagnostic equipment should be managed throughout its full life cycle, from needs assessment and procurement to installation, use, maintenance, replacement, and disposal. Although Uganda has made progress in expanding diagnostic capacity, future efforts should focus more on whether equipment is functional, sustainable, and accessible to the patients who need it most.

5.1 Limitations and Recommendations

This article was based mainly on secondary data, reports, and published literature. Because the condition of medical equipment can change from time to time, the information used may not give the exact current situation in every public hospital. Some facilities may have improved, while others may still be facing serious equipment challenges that were not fully captured in the available sources. There was also no direct physical assessment of diagnostic equipment in these hospitals, which further restricted and biased the results and discussion. For this reason, some regional differences and facility-specific issues may not have been fully identified. In addition, information on equipment downtime, repair costs, maintenance response time, and availability of spare parts was limited, especially because many facilities do not keep complete digital maintenance records. Another limitation is that the article focused mainly on diagnostic medical equipment. Although some of the issues discussed may also affect other hospital equipment, the findings should not be applied to all medical devices without further investigation.

Future work should involve field-based assessments in selected public hospitals across different regions of Uganda. This would help collect first-hand information on the actual condition of diagnostic equipment, including whether machines are

functional, partially functional, or completely out of service. Studies should also examine equipment downtime in more detail. This should include how often machines break down, how long repairs take, the common causes of failure, and how downtime affects patient waiting time, referrals, and service delivery. Future research should include a detailed cost analysis of diagnostic equipment management. This could compare the cost of reactive maintenance with preventive maintenance and show whether planned servicing is more affordable and sustainable in the long term.

There is also need for future work to develop and test a digital equipment inventory system for public hospitals. Such a system could track equipment location, age, functionality, maintenance history, spare-part needs, and replacement timelines. Testing this system in a few hospitals before national scale-up would help identify practical challenges. Further research should assess the role of biomedical engineers and technicians in improving equipment performance. This could include studying staffing levels, skills gaps, training needs, repair response time, and how biomedical personnel can be better supported at facility and regional levels. Further exploration of the impact of infrastructure on diagnostic equipment functionality will be significant. Areas such as power stability, space requirements, ventilation, radiation safety, and environmental conditions should be examined to understand their impact on equipment lifespan and performance. An investigation on the potential of public-private partnerships in equipment maintenance, refurbishment, spare-part supply, and training will be greatly important. This would help determine which partnership models are practical, affordable, and sustainable for Uganda's public health system.

Conclusion

While Uganda has made progress in expanding diagnostic medical equipment in public hospitals, a significant gap remains in ensuring their functionality and long-term sustainability. Despite current challenges, there are opportunities to strengthen diagnostic technology management through innovation. The findings show that decision-making is often driven by initial acquisition costs rather than total life costs, which eventually render the medical equipment non-operational. Limitations in infrastructure, human resource capacity, and poor coordination among stakeholders also constrain the effective use of diagnostic technologies. Addressing these problems calls for a shift towards integrated Health Technology Management approaches that prioritize life-cycle cost analysis and sustainable financing. Future research should focus on quantitative life-cycle cost evaluations, the impact of predictive preventive maintenance strategies, and the scalability of digital equipment management systems, as well as on exploring context-specific frameworks and partnerships that can support sustainable diagnostic services in low-resource settings. In the long run, Uganda's diagnostic capacity will depend on the extent to which it institutionalizes technology management as a core component of healthcare planning. By aligning national strategies with best practices and leveraging digital innovation, Uganda can transform its diagnostic services into a

robust and sustainable system that supports the country's health and development goals.

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Design and Implementation of a Personalized Data Visualization System for Higher Education

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Abstract: This paper outlines the design of a data visualization solution, intended for use in higher education organizations. The data visualization tool allows for effective interaction with complex data through a customized manner that ensures that all representations of data are understandable. The pedagogues, administration, and students can utilize the system in their operations in order to make well-informed decisions.

The system will ensure its relevancy by integrating the feedback of the users and making visualization adaptable based on different roles. This helps in making the system sustainable. Among the important parts of the solution include the use of dynamic dashboards, which provide up-to-date information on different activities, prediction of different patterns and data processing capabilities.

Such solutions should help the users in making decisions based on relevant data.

Keywords: Data Visualazilation, Higher Education, Decision Making

1 Introduction

Assisting people in processing large amounts of information is the primary purpose of data visualization, as human cognitive capacities are limited and data volumes are large [1]. To simplify visualization and help people make effective decisions, data visualization should be produced in a way that allows domain experts to clearly see all problems and solutions [2]. Visualization techniques, in general, are excellent tools for helping people understand information and can facilitate visual thinking by making complex relationships more easily understood [3]. To effectively forecast academic achievement in higher education, providing a clear definition of what constitutes academic success is crucial. In a case study conducted by [4], the utilization of learning analytics dashboard (LAD) interventions by undergraduate students was examined at a public university located in the mid-Atlantic region of the United States. The study found that student understanding is linked to data relevance, accuracy, and context. Our study has led to the conclusion that changes made to the curriculum have affected students' understanding, and this has been facilitated through data visualization. Other researchers conducted a study on HEI data management practices and identified domain policy-makers' knowledge preferences [5]. Choosing appropriate visualization, interaction, and analytical techniques depends on the dimensions of the data. For our study, we focused on numerical data related to student assessments, graduation, and enrollment in different academic years. Visualization techniques that leverage visual perception are useful for converting tracks into visual information [6]. We employed a chart visualization technique, as also used in the study of Zotov et al. (2021), to graphically present information about student evaluations in various subjects. Data visualization can facilitate better analysis of student assessments and lead to informed decisions to improve their performance, as well as to effectively inform students of their performance in different subjects and academic years through up-to-date assessments, comparisons with the class average, and projections of future outcomes. This could potentially lead to better student behavior, based on observations of the graphs.

2 The Visualization Model for Higher Education Data

Information visualization enhances the understanding of information. It addresses the challenge of representing diverse data types for easy transmission and interpretation. The primary objective of any visualization is to assist users in analyzing vast amounts of information. Data can take various forms (e.g., one-dimensional, two-dimensional, multidimensional, hierarchical, and graphical), while visualization can manifest in diverse formats using a range of techniques

(such as standard 2D/3D displays, geometrically transformed displays, icon-based displays, dense pixel displays, and stacked displays).

In the initial case of the study, we possess data concerning student evaluations across various subjects and their graduation years, with a specific emphasis on exploring the correlation between these variables. In the subsequent case of the study, data is organized based on questionnaires concerning the influence of data visualization technology on decision-making processes.

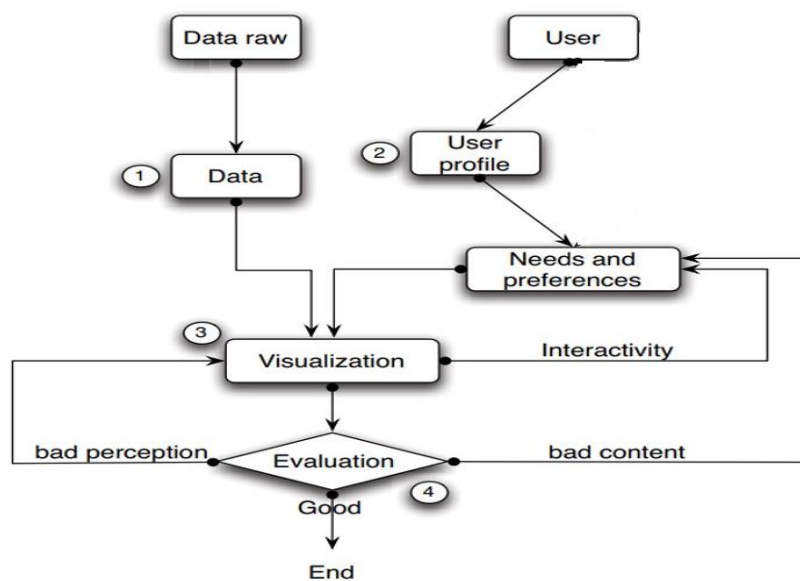


Figure 1
The Visualization Model for Higher Education Data

Figure 1 represents the visualization generation process in four stages that include: 1) Data Preparation based on data collected from raw data sources; 2) User profiling by establishing the user's need and preference; 3) Visualization Generation according to the need and preference of the user; 4) Evaluation of Visualizations to enhance them.

Figure 1 shows the data-based visualization generation and improvement process according to the needs of users. Let us now take a closer look at each part of the figure.

- Raw Data Preparation:

The process consists of cleaning, transforming, and structuring the data in such a way that it becomes useful for the purposes of visualization.

- From Raw Data to Usable Data (Stage 1):

Raw data implies data that has not been processed yet. The data becomes subject to processing in the data preparation block; thus, it becomes useful for visualization. It is the first stage when raw data is transformed into useful information.

- User and User Profile (Step 2):

Users' profiles contain some explicit data such as preferences, goals, or interactions with other users. Such profiles become an input to the "Needs and Preferences" block, where all data are combined and used for personalizing visualization in accordance with user's needs.

- Visualization Generation (Step 3):

The system will generate interactive visualizations after processing the data and understanding what is required by the user. The purpose of such visualizations is to provide data clarity while satisfying the preferences of users.

- Feedback Loops (Step 4):

As soon as visualizations become operational, feedback loops will be able to fine-tune the content and visual clarity.

When bad perception occurs: If the user is dissatisfied with the visualization and finds it difficult to interpret, the feedback loop will correct the visualization for better visual clarity.

When bad content arises: When the content fails to meet the user's requirements, the feedback loop will reassess the preferences and data of the user to fine-tune the content.

If the visualization meets expectations, then the process ends in success.

- Interactivity:

The ability for users to interact with visualizations enables them to engage with data more deeply. Interaction plays an integral role in continuous improvement of visualizations through feedback.

- Continuous Improvement:

Continuous improvement is at the heart of the process in question through feedback cycles. Visualizations will be continually improved, especially if the output does not meet the requirements of the users, in terms of its content and presentation.

To sum up, the picture above provides a framework that illustrates how data visualization should be undertaken, taking into account continuous improvement, data transformation, customization, among other considerations.

3 Data Visualizer Application

The Data Visualizer is a data visualization software allowing users to import data in different formats including .csv, .xlsx, and then visualize data in the form of interactive graphics like line chart, histogram, pie chart, and many others. This software provides customization of graphics and a user-friendly interface suitable for everyone from beginner to expert.

This software acts as a tool for data visualization and file conversion. It was built using the Streamlit framework and allows users to upload CSV files for visualization, apply dynamic filters on them, and customize plots. Moreover, this software converts XLSX files to CSV files.

The key elements of this system are the possibility to represent CSV data in interactive graphs and the dynamic filtering of data through the sidebar. Furthermore, this system has the capability of converting XLSX data into CSV files, as well as modifying the datasets and downloading them in their new form. One of the capabilities of the system is the creation of different kinds of graphs, including bar, line, scatter, and pie graphs. Additionally, users have the possibility to adjust the visualization in terms of its colors, scale, labeling, and other parameters. The system also allows exporting the visualized graphs into PNG files, in addition to offering an intuitive interface.

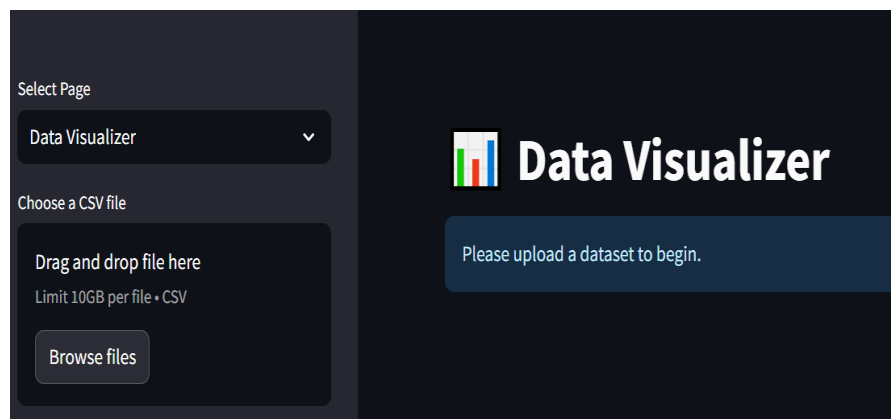


Figure 1
Home Page of the Data Visualizer Application

The important libraries that have been implemented in the development process of this project include Streamlit, which creates a web interface, and Pandas, which manipulates and analyzes the data. Chardet has been used to determine the file encoding, while Plotly has been used to create dynamic charts. Finally, Xlsx2csv has been used to convert files in XLSX format to CSV format.

Plot Type	Data Type	Description
Histogram	Numeric	Displays the distribution of numeric data by grouping into bins.
Box Plot	Numeric	Shows the distribution of data based on five summary statistics(min, Q1, median, Q3, max).
Boxen Plot	Numeric	A variation of a box plot, showing more details about the tails of the distribution.
Heatmap	Numeric	Displays the data values using color scales in a matrix format.
Bubble Chart	Numeric	A scatter plot with an additional size variable to represent another dimension.
Density Plot	Numeric	Shows the distribution of numeric data using a density contour plot.
Violin Plot	Numeric	Combines a box plot with a kernel density estimate, showing data distribution.
3D Scatter Plot	Numeric	A scatter plot in three dimensions (X, Y, Z axes).
Bar Plot	Numeric	Displays data using bars, where the length of each bar is proportional to the value.
Bar Chart	Categorical	Displays data using grouped bars for each category.
Pie Chart	Categorical	Shows parts of a whole as slices of a pie.
Sunburst	Categorical	Represents hierarchical categories in a circular diagram.
Dot Plot	Categorical	Plots dots along an axis for each category to show frequency or value.
Heatmap	Categorical	Displays categorical relationships in a matrix using color.
Treemap	Categorical	Displays hierarchical data as nested rectangles.

Table 1
Supported plot types

The table represents an overview of plot types utilized in data visualization, data type, and functions. Plots represent the way visual information is created; hence,

there are two main types of plots – for numerical and categorical data. The first column contains plot names, the second one specifies what type of data they work with, either numerical or categorical, and the third one contains descriptions of those plots. As can be seen from the table, almost all plots work with numerical data showing distribution, comparisons, and relations between data. Thus, the histogram is used to show the distribution of data in bins (intervals of values), while box plots show the distribution of data statistically (the minimum value, lower and upper quartiles, and maximum value). Box plots give an opportunity to get more detailed information about the tails of the distribution. In turn, the bar chart is utilized for categorical data to make comparisons. Various plots can be used depending on what kind of data is analyzed, which allows analyzing distributions, making comparisons, and revealing connections between data. Visualizing data is an important step that makes its analysis easier.

4 Utilization of the Application at Logos University College

An Executive Information System (EIS) for higher education is one of the critical means that enables university and college managers to gather and analyze data about their organization's performance in terms of academic excellence, financial situation, and efficient work of the university. EIS gives managers an overall picture regarding different functions within a university or a college such as student enrollment, academic achievements, financial status, and employees' job performances.

For instance, in order to improve their academic performance as well as their management of operations, the EIS known as Data Visualizer for Strategic Management is used in "Logos" University College. The top managers of the university require quick and simple ways of getting information on their students, faculty members, and financial management of the institution.

Important EIS functions in Logos University College:

1. Student Enrollment Monitoring: Visualization: An interactive display illustrates the number of new enrollments during a year and their percentage among the overall number of enrolled students. This data can be filtered according to the specific faculty or study program.

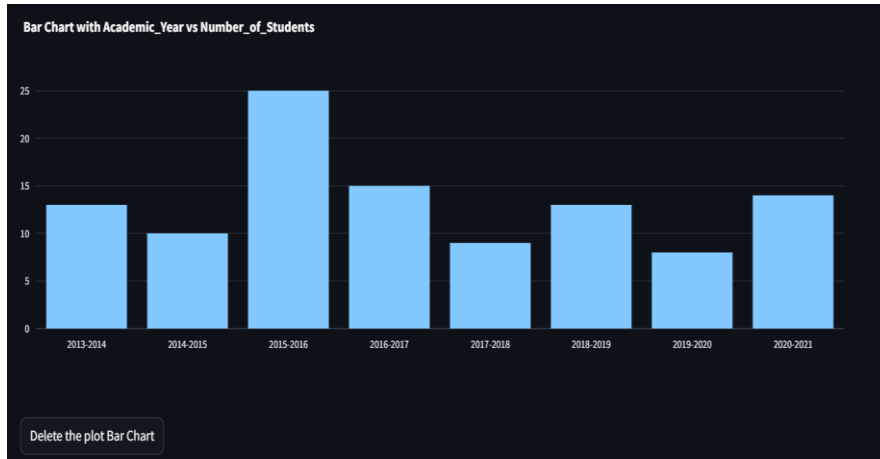


Figure 2
Student Enrollment in the Applied Informatics Study Program

The bar graph shown in figure 2 illustrates an unstable dynamics for the number of students over the years due to considerable changes and lack of long-term linearity. The first decline is seen during 2013-2014 to 2014-2015 years; then, there occurs an abrupt increase at 2015-2016 year. The latter may be associated with different reasons such as growing interest in the program, favorable policies for admission, or other. Then, the chart displays a constant decrease up to 2017-2018 year; in this case, we may say about decreasing demands and impact of some external factors (e.g., migration, competition, or others). The next years show only a small growth, but unstable one because it decreases at 2019-2020 year and rises at 2020-2021 year. Therefore, the analysis of dynamics demonstrates that the admission process is sensitive to external factors.

2. Student Academic Performance: Visualization: Graphs depicting grade distribution in each faculty and department will be available to aid in identifying areas that require further attention. Performance Comparison: Student performance will be compared to previous performances to identify academic trends.

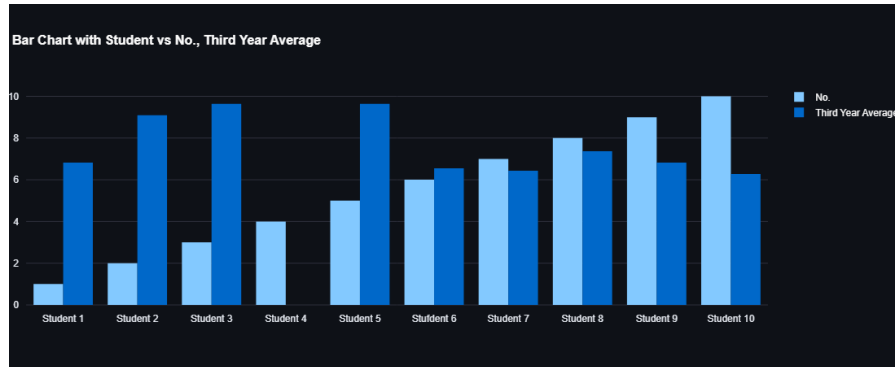


Figure 3
Performance of Applied Informatics Students in Third-Year Courses

Figure 3 shows the average marks for the third year of students, who are assigned numerical codes for anonymity purposes. Based on the analysis performed in terms of the graph above, it can be stated that the students have relatively stable averages and are positioned in a narrow range of performance, which indicates a rather good balance in academic achievements. At the same time, there are some differences in performance: the student with code number 3 demonstrates the best performance in the group, having the highest mark average, while the student with code number 10 has the lowest performance with the worst mark average compared to others.

3. Budget Planning: Visualisation: There will be a visual representation of the sources of funds like tuition fees, government and donor contributions. One will also be able to see where money is spent in terms of salaries, infrastructure, and research. Financial Projections: The system will enable one to conduct "what if" analysis like seeing what the effect would be if one raises tuition fees or invests heavily in infrastructure.
4. Performance Analysis: Visualisation: The system has a dashboard where one sees publication rates of academics, number of research projects undertaken by faculty members and staff, and fund allocation for research activities. Improvement Opportunities: In case of a faculty member not publishing much research work, then the system signals that a mentorship or training programme is required.
5. Placement of Graduates: Visualisation: The system uses a graph to show the percentage of students getting employed within six months after completing their studies.

Conclusions

In the course of the research presented in the article, a data visualization system was developed on the basis of the concept of an Executive Information System (EIS). Namely, the Data Visualizer system was utilized for designing this solution.

The data visualization system introduced in the research showed the well-designed and efficient structure of the platform since various data sources were integrated and represented using visualization tools. In particular, visual panels (dashboards) allowed one to visualize grades' averages, distributions, as well as comparison between students or even groups of students.

The visualizations provided in the article clearly demonstrated how the system functions in practice helping users to identify certain trends, average results, and cases requiring special attention. Thus, it helps improve the decision-making process for both educational and administrative personnel.

Among the major strengths of the system, one can mention high level of flexibility and versatility of the solutions provided.

Concluding, one should say that the utilization of the system discussed in the article proves how important the application of data visualization techniques can be. As the further direction for research, the incorporation of analytical tools, such as predictive modeling or artificial intelligence algorithms, is suggested.

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The role of small and medium-sized enterprises (SMEs) in the manufacturing sector, their competitiveness, and challenges in Ghana

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Abstract: Small and Medium-sized Enterprises (SMEs) form the foundation of the Ghanaian economy, and in this regard, manufacturing SMEs are vital in structural change, the generation of employment, and value addition. This study investigates how manufacturing SMEs contribute to diversification and economic growth and elaborates on the competitive and structural forces that define the performance and future competitiveness of manufacturing SMEs. The analysis directly relates to how manufacturing SMEs contribute to the Gross Domestic Product (GDP), employment, and industrial upgrading, working in the conditions of stiff competition and structural limitations. This study relies on secondary sources related to the Ghana Statistical Service, government reports, publications from the financial sector, previous research, and academic findings of Ghanaian SMEs. The SWOT analysis and Porter's 5 forces framework were employed with descriptive statistical analysis to evaluate the roles of SMEs, industry trends, and competition within their operational environment. The study concludes that manufacturing SMEs are the critical drivers of shared economic prosperity, creation of jobs, and diversification in the manufacturing sector in Ghana, but their potential is underexploited. To enhance their competitiveness, there should be consistent policy actions that increase access to finance, modernize infrastructure, assist with standards and quality systems, and promote innovation and strategic capability that will empower manufacturing SMEs to promote sustainable and resilient economic transformation.

Keywords: Small and Medium-sized Enterprises; Ghana Enterprise Agency; Gross Domestic Product; Manufacturing Value Added; Competition; Diversification.

1 Introduction

According to Global National Action Plans on Business and Human Rights, Small and Medium Enterprises (SMEs) are non-subsidary firms that have a limited number of employees, fewer than a given number. They also emphasized that SMEs could be defined based on financial criteria: in the European Union, SMEs should generate a turnover of less than EUR 40 million per annum and/or a balance-sheet valuation of less than EUR 27 million. Although the definition of a small and medium enterprise (SME) may be different in various institutions and may also change with time. The Ghana Enterprise Agency (GEA) defines an SME as an enterprise with fewer than 10 employees and fixed assets such as plants and machinery with a total amount under 10 million Ghanaian Cedis [1].

The SME Support Services Strategy report published by the Ghana Enterprise Agency, out of the estimated number of 2.1 million businesses in Ghana, about 1.7 million of them can be classified as small and medium-sized enterprises (SMEs) [2]. These are businesses that are dynamic in nature, with a vibrant mix of local talent and innovation, as well as entrepreneurial spirit, that have the potential to make a significant contribution to the growth and development of the Ghanaian economy. SMEs are highly regarded as being crucial in job creation and economic growth, having a contribution of more than half of the global employment and a contribution towards the output of the private sector when evaluated against Gross Domestic Product (GDP) [3]. In Ghana, SMEs are even more important, with a high employment rate and greater output of the private sector. Moreover, approximately, it is estimated that 92% of the businesses in Ghana fall under the SMEs category, which is similar to the global average [1].

The economic importance of SMEs in Ghana has been large, and the recent official records indicate that these enterprises contribute the highest to the national GDP growth of the country and to the national total employment. More specifically, research indicates that SMEs are important in the manufacturing industry, where the highest percentage of all manufacturing employment opportunities is being created by small and medium-sized enterprises [4]. This notwithstanding, SMEs in the manufacturing sector play a pivotal role in diversifying economies and value addition. More so, process innovation not only increases productivity but also equips SMEs to react more to the changing market demands. This supports the fact that competitive environments create a culture of continuous improvement that is very crucial in maintaining business performance.

The impacts of competition in the market on the performance of small and medium-sized enterprises (SMEs) have been studied in detail using experimental research within different settings. Various surveys have also revealed a relationship between the level of competition in the market and the main performance indicators of SMEs, such as profitability, market share, and growth. A longitudinal study has indicated that increased competition may lead to a higher rate of failure among the

small and medium-sized enterprises (SMEs), more so among those that are not equipped with the necessary resources and capabilities to compete favourably [5]. Conversely, in developed countries, the SMEs enjoy less preferential treatment in terms of the regulatory frameworks and accessibility of resources, which may be used to reduce the adverse effects of competition. Nevertheless, their performance is determined by a combination of factors, including competition in the market, innovation, and strategic orientation. Among the important factors that determine the performance of SMEs is market competition.

This study aims to investigate the role small and medium-sized enterprises (SMEs) play in the growth of the Ghanaian economy and explore the factors that determine or influence their competitiveness in the manufacturing industry.

The main findings of this study could facilitate potential investors and other stakeholders investigating the opportunity in manufacturing SMEs. The study will serve as an excellent tool for SME owners and managers who intend to improve the overall performance of their organizations or businesses by applying the Total Quality Management practices. In addition, the results and recommendations of this study will provide fundamental learning to the stakeholders in the manufacturing sector and guide government policies that will enable healthy and sustainable development among SMEs in the manufacturing sector. Eventually, the results of this research will enhance academic knowledge and literature, which will benefit both the researchers and students interested in the role of manufacturing SMEs and their competitiveness in various regions.

2 Literature Review

SMEs are described as the mainstay of Ghana's economy, accounting for about 90–92% of registered firms, roughly 70% of GDP, and the majority of private sector employment [4]. These enterprises are particularly dominant in labour-intensive segments such as food processing, light manufacturing, retail trade, and personal services, where low entry barriers and modest capital requirements encourage widespread participation. The SME-intensive structure has fostered entrepreneurship and job creation but has also produced a fragmented productive base characterised by small firm size, weak capitalization, and limited technological capability. Moreover, research has identified that SMEs are compelled by the competitive forces to assume strategic orientations that enhance their performance [6]. The results show that SMEs that use proactive competitive policy approaches, such as differentiation and cost leadership, are more prone to attain positive results in the market. The research underlines the importance of adopting new practices to streamline operational procedures and achieve customer retention. Within this broader SME landscape, manufacturing SMEs play an essential role in value addition, non-traditional exports, and structural transformation. Evidence reviewed

by Yeboah indicates that Ghana's manufacturing sector contributes a modest and relatively stagnant share of GDP, yet SMEs provide the bulk of industrial employment and a large proportion of output in subsectors [9]. The competitive force would encourage SMEs to be innovative and improve their efficiency in operations. Also, the strategic orientation, allocation of resources, and innovation capabilities are major factors that influence the performance of the SMEs [7]. This advocates the need to have a holistic approach that will focus on not only internal strengths but also external market environments to improve the performance of manufacturing SMEs. This supports the fact that competitive environments create a culture of continuous improvement that is very crucial in maintaining business or enterprise performance.

Recent national and donor-supported programs in Ghana, such as SME competitiveness initiatives, industrial parks, and targeted financing schemes, have been introduced to ease long-standing constraints facing firms in the manufacturing sector. These interventions seek to expand access to credit, strengthen business development services, and foster export readiness, thereby positioning small and medium-sized enterprises (SMEs) to participate more effectively in domestic and international markets. Evaluative evidence indicates that these programs have begun to improve managerial capacity and market access for a subset of SMEs, but their overall impact is muted by limited coverage and weak coordination across implementing agencies, which leaves many manufacturers outside formal support systems.

The existing literature underscores several critical gaps in understanding how these policies shape outcomes for manufacturing SMEs. Most studies treat SMEs as a homogeneous group, paying insufficient attention to the distinctive challenges and opportunities of manufacturing firms, and only a few undertake firm-level analyses that explicitly focus on this segment of the economy.

Addressing these gaps is vital for designing evidence-based interventions capable of transforming the numerical dominance of manufacturing SMEs into sustained competitiveness and deeper structural change in the Ghanaian economy. This study, therefore, undertakes an empirical investigation of the roles that manufacturing SMEs play in Ghana's economy, with particular emphasis on how their competitiveness shapes industrial performance, employment creation, and broader structural transformation.

3 Data and Method

This chapter outlines the data sources and methodological approaches used in analyzing the role of manufacturing SMEs in Ghana's development and the impact of their competitive environment. The analysis is based on the secondary data and

existing literature obtained through Scopus and Web of Science publications and other official reports by the Ghana Statistical Service (GSS), such as national accounts and productivity reports [4], [8], [9], [10]. The government and institutional sources were also used to obtain additional data, including the Ghana Ministry of Finance press releases and the SME reports of the Ghana Community Banks, which present aggregate statistics on the SMEs [2], [11], [12]. Also, qualitative data were obtained through academic and industrial research on Ghanaian SMEs.

To perform the analysis, descriptive techniques were used to highlight the roles of manufacturing SMEs and to investigate current trends. A SWOT analysis was also used to determine the internal strengths and weaknesses and external threats and opportunities of manufacturing SMEs. This is a strategic planning model that helps businesses analyze their competitive position and determine what to do to grow. Also, Porter's Five Forces model was used to analyze the competitive forces, such as supplier and buyer power, threat of new entrants, substitutes, and industry rivalry. These are the established models of strategic management that have been highly applied in the research of SMEs. Through combining information with these theoretical models, the competitive environment of Ghana's manufacturing SMEs was systematically explained.

4 Results

This chapter presents the key findings on the role and performance of manufacturing SMEs in Ghana's economy. It highlights their contributions to GDP, employment, and sectoral output, focusing particularly on manufacturing SMEs as drivers of industrialization and growth. The analysis is based on recent national data and literature, offering insights into structural trends, value addition, and sectoral composition that define the country's economic landscape.

4.1 SMEs' Share of Ghana's Economy

Small and Medium-sized Enterprises (SMEs) occupy a central position in Ghana's economic structure, accounting for a substantial share of national output, employment, and business activity. The data from Table 1 suggests that the economy of Ghana relies heavily on the small and medium-sized enterprises (SMEs). The data shows the major contributions of SMEs, which occupy about 70% of the Gross Domestic Product (GDP) of the country and approximately 80% to 85% of all employment in 2024 [11]. The contribution of SMEs, especially in the manufacturing industry, is exclusively significant, as they create approximately 85% of all jobs in the manufacturing industry, and they are a significant majority of manufacturing firms.

Contribution Type	Approximate Value (%)
SME share of national GDP	70%
SME share of total employment	80% - 85%
SME share of manufacturing employment	85%
SMEs as % of registered businesses	92%

Table 1
SMEs' Share of Ghana's Economy (2024)
Source: based on literature[4]

Additionally, the data suggests that a significant portion of economic activity is driven by SMEs. The Ghanaian economy is dependent on SMEs that make about 70% contribution to the GDP of the country. Nevertheless, their competitiveness in the international markets is curtailed by a few challenges.

The SMEs are critical in the economic environment of Ghana, especially in the manufacturing industry. They not only drive the economy but also serve as drivers of job creation, diversification of the economy, and innovation. SMEs in the manufacturing sector alone contribute approximately 85% of their employment, which creates a vast network that is a key source of jobs in Ghana. These businesses offer a living to a large proportion of the population, particularly in urban and peri-urban regions. Manufacturing SMEs can reduce poverty by absorbing a large percentage of the labour force and assist in reducing unemployment.

4.2 Manufacturing Sector Value Added to the GDP

Manufacturing sector value added to the GDP reflects the share of total national output that comes from manufacturing entities between 2015 and 2024, and it is a key indicator of how strongly manufacturing enterprises contribute to Ghana's structural transformation and economic growth.

Year	Manufacturing Sector Value Added (% of GDP)
2015	12.4
2016	12.1
2017	11.8
2018	11.3
2019	11.0
2020	10.7
2021	10.5
2022	10.3
2023	10.2
2024	10.1

Table 2
Manufacturing Sector Value Added as % of GDP (2015 - 2024)
Source: based on literature [13]

The data from Table 2 shows that the ratio of manufacturing value added (MVA) to GDP has declined, and this has fallen by approximately 2.3% points over a decade [13]. Nevertheless, its share began to drop to less than 11% in 2018. In 2020, the COVID-19 lockdowns and border closures caused the closure of factories and raw material shortages. Even though the fall in output was partially compensated by growth in food processing, production of sanitary products and other essential products, the MVA dropped to 10.7% in 2020. Although the GDP made a comeback beyond 2021, it was the fastest recovery of the service sector, and that of manufacturing remained at a declining share, having hit 10.1% by 2024, even as the total volume of production rose.

Manufacturing has always been known as the foundation of structural change and economic independence. In the case of Ghana, where the country has a lot of natural resources but relies heavily on the export of commodities, the growth of the manufacturing sector is essential to accomplish value addition, diversifying exports, and industrial employment. Between 2015 and 2024, the manufacturing sector's contribution to Ghana's GDP has slowly decreased from 12.4% to 10.1%. This trend is an indicator of a low rate of industrialization relative to an increase in the services

industry and the instability of extractive industries. It highlights the need to have more competitive small and medium-sized enterprises (SMEs) to drive growth.

Ghana has natural resources and a strategic geographic location, which provide a foundation for value addition through manufacturing. The sector has historically been the source of structural economic transformation, with established sub-sectors like food processing and essential goods production that helped offset declines during shocks like Covid-19. The manufacturing sector benefits from rich natural resources, a growing urban population, and government initiatives to promote industrialization, positioning it as a potential driver of value addition and economic diversification. However, the sector has seen its share of GDP fall from 12.4% in 2015 to 10.1% in 2024, reflecting persistent weaknesses such as infrastructure gaps, unreliable energy supply, high costs of capital, and dependence on commodity exports. Opportunities lie in emerging markets, agro-processing, renewable energy, and greater regional access via the African Continental Free Trade Area (AfCFTA), while threats include global market volatility, competition from imports, slow technological adoption, and challenges posed by regulatory and environmental risks. These dynamics highlight the urgent need for strengthening manufacturing SMEs, fostering innovation, and improving supporting infrastructure so that manufacturing can better contribute to Ghana's structural transformation.

4.3 SME Contribution to Gross Domestic Product

The contribution of Small and Medium-sized Enterprises (SMEs) to Ghana's Gross Domestic Product (GDP) captures how much of the country's total economic output is generated by these firms, highlighting their central role in driving production, income creation, and overall economic growth.

Year	SME Contribution to GDP (%)
2015	68.0
2016	68.5
2017	69.0
2018	69.2
2019	69.5
2020	69.7
2021	70.0
2022	70.0
2023	70.2
2024	70.3

Table 3
SME Contribution to GDP (2015 - 2024)
Source: based on literature [12], [13]

The data in Table 3, which tracks the contribution of Small and Medium-sized Enterprises (SMEs) to Ghana's Gross Domestic Product (GDP) between 2015 and 2024, shows a steady increase from 68.0% to 70.3% [12], [13]. This upward trend indicates both the expanding scope of SME activities and the growing dependence of national output on these firms, even in the face of domestic and global shocks. SMEs, including those in manufacturing, therefore play a stabilizing role by maintaining and gradually increasing their share of economic activity, diversifying across sectors, and reducing the risks associated with heavy reliance on large enterprises or single-sector growth. For policymakers, the pattern underlines the need to nurture a strong SME base, particularly manufacturing SMEs, as a buffer against economic volatility and as a driver of inclusive growth.

Although the data table does not suggest employment directly, the rising GDP share implies that SMEs are major job creators, supporting incomes and social stability in urban, peri-urban, and rural communities. Manufacturing SMEs, embedded in these figures, add value by processing raw materials, assembling products, and feeding local value chains, thereby promoting industrialization and "Made in Ghana" products. Their investments in plants, equipment, and labour help strengthen local

economic ecosystems and create a virtuous cycle of production and reinvestment. At the same time, the relatively average annual growth of about 0.26 percentage points suggests persistent challenges such as limited finance, technology gaps, infrastructure constraints, and skills shortages. This slow but positive increase signals both gradual improvement and significant untapped potential that targeted interventions in areas like taxation, regulation, infrastructure, education, and access to finance could unlock.

4.4 Structural Composition of SME Output

The structural composition of SME output describes how small and medium-sized enterprises distribute their economic activities across different sectors, showing the relative contribution of agriculture, manufacturing, services, and construction to Ghana’s sectoral GDP.

Sector	Approx. SME Share of Sectoral GDP (2024)	Key Activities
Agriculture & Agro-processing	65%	Cocoa, cassava, fruits, and palm oil
Manufacturing	70 – 75%	Food/beverages, textiles, wood, light metals
Services	72 – 78%	Retail, CT, transport, hospitality
Construction	55 – 60%	Building materials, civil works

Table 4
Structural Composition of SME Output (2024)
Source: based on literature [4]

The data from Table 4 presents important insights into the structural composition of SMEs' output in Ghana across various sectors in 2024, highlighting their approximate contributions to sectoral GDP and key activities. The SME sector is predominantly characterized by Agriculture and Agro-processing, Manufacturing, Services and Construction. Their contribution to sectoral GDP is significant, underscoring their status as the backbone of the economy and vital contributors to employment, income generation, and overall economic activity.

Manufacturing SMEs account for a considerable share of the sector’s GDP, contributing approximately 70-75% [4]. These enterprises primarily focus on the production of food and beverages, textiles, wood products, light metals, and other products. This highlights their critical role in adding value to raw materials, promoting industrial diversification, fostering local production, and reducing dependence on imports. Additionally, their contributions support downstream sectors like retail and export, thereby enhancing Ghana’s industrial growth and economic resilience.

Furthermore, the data indicate that manufacturing SMEs in Ghana are very significant in driving industrialization and economic development by creating jobs, encouraging entrepreneurship, and supporting GDP growth in this essential sector. The dominance in the manufacturing sector reinforces their significance in improving national productivity and increasing competitiveness at both local and global levels. Therefore, SMEs, particularly those in the manufacturing sector, emerge as vital players in Ghana’s economic landscape in 2024 and beyond, shaping growth trajectories and developmental outcomes.

4.5 Employment Share by SME Sectors

Employment share by SME sectors captures how jobs are distributed across different parts of Ghana’s economy and highlights the dominant role that manufacturing, construction and service-oriented SMEs play in absorbing the labour force compared with large enterprises in their respective sectors.

Sector	SMEs Approx. Share of Sector Employment (%)	Large Enterprises Approx. Share of Sector Employment (%)
Manufacturing	85%	15%
Services	60%	40%
Agricultural	45%	55%
Construction	75%	25%

Table 5
Employment Shared in Various Sectors (2024)
Source: based on literature [11], [13]

The data in the data in Table 5 shows the employment share of SMEs and large enterprises across key sectors for the 2024 calendar year. Employment distribution

serves as a crucial indicator of economic structure and development. In Ghana, Small and Medium-sized Enterprises (SMEs) continue to be the primary source of job creation, highlighting the economy's strong dependence on private-sector dynamism rather than large-scale industry. As detailed in Table 5, SMEs in the manufacturing sector account for approximately 85% of their sectorial employment, followed by SMEs in construction at around 75%, in services at 60% and agricultural 45%, with large enterprises contributing about 15%, 25%, 40% and 55% of various sector employment, respectively [11], [13]. This employment structure is common in developing economies characterized by a significant informal sector and limited industrial automation. While it emphasizes the critical role of SMEs in job creation, it also reveals vulnerabilities related to productivity, job quality, and wage stability. According to the Ghana Statistical Service, total employment in 2024 was estimated at 11.8 million workers, with SMEs employing over 9.5 million of them [13]. Within the manufacturing subsector, SMEs primarily dominate segments such as food processing, wood products, textiles, and metal fabrication, collectively taking up most industrial work. This dominance of Manufacturing SMEs, with approximately 85% of employment share, can be explained by the fact that the number of labour-intensive companies manufacturing in response to local markets is quite large.

5 Discussion

5.1 Concluding Remarks

This study revealed that manufacturing SMEs remain dominant in employment and national value creation, and therefore, the competitive environment is both economically and socially consequential. It revealed that SMEs contributed approximately 70% of GDP and accounted for 85% of manufacturing employment in the 2024 calendar year. These high shares mean that competition among manufacturing SMEs not only determines business survival but also livelihoods for millions of workers. In short, competition that forces manufacturing SMEs to fail risks large employment losses. On the contrary, competitive pressure that spurs upgrading can have large positive spillovers for productivity and jobs. Facing price competition from imports and rivalry among many small domestic firms, SME owners have been pushed to cut waste, adopt leaner processes, and search for lower-cost inputs. This is supported by the Ghana Statistical Service, 2024 Labour Survey: Statistical Year Overview, that competitive pressure encouraged cost-saving responses, including partial automation, supplier consolidation, and increased attention to inventory management among better-performing SMEs [4].

Additionally, manufacturing value added within the decade fell from roughly 12.4% of GDP in 2015 to about 10.1% in 2024. This decline matters for competition because a smaller manufacturing sector reduces domestic demand for intermediate goods and increases competitive pressure on surviving firms to capture limited market shares. A shrinking sector share does not necessarily indicate absolute contraction, but because GDP and services expanded faster, manufacturing SMEs faced more intense rivalry for the local market and stronger pressure from cheaper imports competing on price and variety. This persistent import competition is a principal driver forcing manufacturing SMEs either to reduce margins or to find niches via quality or brand differentiation.

Also, the study highlights that many manufacturing SMEs operate in informal or semi-formal settings, rely on low-technology equipment, and face high input costs, unreliable infrastructure, and intense import competition, all of which limit productivity and keep a large share of activity in low-value segments. Competitive pressures have a dual effect; they raise the risk of firm exit and employment loss for weaker SMEs, but they also push better-positioned enterprises to cut waste, upgrade processes, and seek differentiation through quality, branding, or niche markets. This dynamic explains why some manufacturing SMEs manage to leverage competition into efficiency and innovation gains, while others remain trapped in survival mode with little capacity to invest in modernization. This agrees with the findings of K. Issau, I. S. K. Acquah, R. I. Gnankob, and Z. Hamidu, on their studies on Innovation orientation and performance of small and medium-sized enterprises (SMES) in Ghana [10].

Again, the findings indicate that Ghana's manufacturing future is tightly bound to whether manufacturing SMEs can transition from numerically dominant but structurally weak actors into competitive, technology-enabled producers capable of sustaining higher value-added output. Realizing this transition requires more than firm-level effort; it depends on a supportive competitive environment that reduces structural bottlenecks, improves access to finance and skills, and rewards innovation rather than informality or market power. Without such changes, the declining share of manufacturing in GDP, combined with persistent import pressure, will continue to intensify rivalry over a shrinking domestic base, risking job losses and underutilizing the country's entrepreneurial capacity. This claim is supported by studies conducted by G. Asare, A. B. Amankwah, and P. Ankoma on the challenges facing small and medium-scale enterprises in Ghana, with a case study of the textile industry. [14].

5.2 Quadrant SWOT Matrix for Ghana's Manufacturing SMEs (2024)

Ghana's manufacturing small and medium-sized enterprises (SMEs) constitute the central pillar of the country's industrial economy, providing the bulk of output,

employment and value addition. Their numerical dominance, extensive regional presence and strong local linkages make them central to structural transformation, yet persistent internal constraints and a challenging external environment shape a complex competitive landscape that warrants systematic SWOT analysis.

Strengths	Weaknesses
SMEs contribute around 70% of the national GDP, underscoring their macroeconomic significance for economic development and growth.	High prevalence of informality and semi-formality weakens organizational stability and regulatory compliance.
Manufacturing SMEs account for about 85% of employment in their sector, indicating strong labour absorption capacity.	Heavy concentration of employment in manufacturing SMEs increases vulnerability to manufacturing SMEs' failure and sectoral shocks.
Numerical dominance and strong local embeddedness across regions or semi-urban areas support decentralized industrial activity.	Reliance on low-technology equipment and outdated production processes suppresses productivity and product quality.
Manufacturing SMEs facilitate economic diversification, non-traditional exports and community-level value addition.	Chronic undercapitalization and restricted access to affordable long-term finance limit expansion and technological upgrading.
Manufacturing firms serve as key vehicles for inclusive growth and for spreading the benefits of industrialization across regions and social groups.	Infrastructure bottlenecks and unreliable energy supply raise production costs and hinder the achievement of economies of scale.

Table 6
Internal Factors on Manufacturing SMEs

Opportunities	Threats
Expanding domestic demand creates scope for increased sales of processed foods, light manufactures and related products in the manufacturing sector.	Intense price competition from cheaper imported products erodes local market share and compresses already thin margins in the manufacturing firms.
African Continental Free Trade Area (AfCFTA) and other regional frameworks open larger African markets for SME-produced goods.	Regulatory gaps and weak enforcement of competition rules allow market manipulation and favour entrenched interests.
Government programs, industrial parks and targeted financing schemes support technology adoption and capacity building in the manufacturing SMEs.	Macroeconomic volatility, including currency depreciation and global input price shocks, raises business risk and cost pressures on SMEs.
Potential to introduce appropriate technologies and partial automation to raise productivity without large-scale job losses.	Persistent external pressures may force weaker manufacturing firms to exit, with adverse implications for employment and local incomes.
Opportunities to move into higher value-added niches and participate more effectively in regional and global value chains.	Failure to upgrade technologically and meet standards risks locking manufacturing SMEs into low-value market segments.

Table 7
External Factors on Manufacturing SMEs

The SWOT matrix highlights that Ghana's manufacturing SMEs occupy a structurally core yet competitively fragile position within the national economy. Their strengths lie in their dominant contribution to Ghana's GDP, employment and regional value addition, as well as their role in promoting inclusive industrialization across diverse communities. These attributes make them indispensable to structural transformation and broad-based development. However, pervasive informality, weak managerial systems, technological obsolescence and chronic undercapitalization undermine their ability to translate numerical dominance into sustained productivity and competitiveness.

Externally, expanding domestic demand, regional integration under AfCFTA and targeted policy interventions create a favourable opportunity structure for upgrading, market diversification and deeper value-chain participation. At the same time, intense import competition, regulatory weaknesses and macroeconomic instability constitute serious threats that can erode margins, discourage investment and precipitate firm exit. Strategically, this configuration implies that policy efforts

must focus on formalization, financial deepening, infrastructure reliability and capability development, while firm-level strategies prioritize innovation, quality assurance and branding. Only by simultaneously addressing internal constraints and external risks can Ghana's manufacturing SMEs shift from survival-oriented competition to a more dynamic trajectory of technological upgrading and long-term competitiveness.

5.3 Porter's Five Forces Analysis on Ghana's Manufacturing SMEs

Porter's Five Forces framework is applied in this study to characterize the competitive pressures facing manufacturing SMEs in Ghana and to complement the descriptive and SWOT analyses. The empirical evidence on GDP shares, employment, import penetration and firm structure indicates that rivalry among existing competitors is intense: numerous small and fragmented SMEs compete in a slowly expanding manufacturing sector whose value added has declined from about 12.4% to 10.1% of GDP between 2015 and 2024, while cheaper imports further compress margins. Under these conditions, competition is often driven by price and survival rather than by productivity-enhancing innovation or deliberate differentiation strategies.

The threat of new entrants is assessed as medium to high. Many manufacturing subsectors in which SMEs operate, such as food processing, light assembly and simple consumer goods, require relatively modest capital and technology, allowing new firms to enter, including through informal or semi-formal channels. At the same time, high borrowing costs, infrastructure gaps and limited access to long-term finance restrict the ability of potential entrants to reach efficient scale, which moderates but does not remove entry pressure. Policy incentives for SME development and industrial parks may also attract additional entrants in targeted places, adding to competitive intensity.

Buyer power is generally high. Domestic buyers, including wholesalers, retailers and public procurers, are highly price-sensitive and can substitute locally produced SME outputs with imported goods whenever local producers cannot match price, quality or reliability. The fragmented structure of the SME segment prevents most firms from exerting countervailing power, and only a limited number can meet the volume, standards and certification requirements demanded by large buyers. This environment enables powerful buyers to squeeze margins and shift risks onto smaller manufacturers, reinforcing the need for differentiation and quality upgrading.

Supplier power and the threat of substitutes also weigh heavily on Ghana's manufacturing SMEs. Many manufacturing SME firms rely on imported inputs and equipment, making them vulnerable to exchange-rate fluctuations and global price shocks, while domestic energy and logistics providers often operate as

quasi-monopolies, constraining manufacturing SMEs' bargaining power and raising production costs. At the same time, a broad spectrum of imported finished products, and in some cases service-based alternatives, directly substitutes local SME output, especially where local quality assurance and branding remain weak. In combination, these forces create a competitive environment in which manufacturing SMEs face strong rivalry, powerful buyers and substitutes, and non-trivial supplier constraints, underscoring the importance of robust competition policy, industrial upgrading and targeted support to translate SME numerical dominance into sustainable competitiveness.

Limitations and Suggestions

While Small and Medium Enterprises (SMEs) in the manufacturing sector play a crucial role in driving economic growth, employment, and innovation in Ghana, they face a range of interconnected challenges that hinder their competitiveness. Key issues include limited access to credit and business development services, a weak institutional and regulatory framework, difficulties in meeting production standards, restricted export opportunities and challenges in implementing Management Systems Standards.

Moreover, the Ghana Private Sector Development Strategy I and II have also identified some serious limitations to SME development in Ghana: the poor investment environment, poor entrepreneurial culture, access to capital, and high capital cost to SMEs, poor support by the institutions of the private sector, poor legal and regulatory environment, and inadequate SME support infrastructure [2]. The Association of Ghana Industries Afro Barometer Report further provided the main causes of failures of small businesses which are; high electricity prices, costly credit, limited access to credit because of collateralizing of credit and waiting payment, lack of awareness of the policy and regulatory landscape, lack of knowledge of quality and standards requirements, poor government procurement practices, inability to access the export markets, inability to meet large orders, lack of export finance schemes, unorganized National Quality Infrastructure and cultural and lifestyle factors that hinder the development of local SMEs [15].

The future of manufacturing SMEs in Ghana appears promising, provided that existing challenges are addressed and supportive measures are strengthened. It is recommended that continued investment in infrastructure, access to finance, and capacity building should empower SMEs to enhance their productivity and competitiveness, while fostering a culture of innovation and entrepreneurship will enable them to develop solutions tailored to local and regional markets, thereby driving sustainable economic growth. Programs offering guidance on export processes, product development, market intelligence, and business planning are essential, just as investments in logistics, energy supply, and communication technology can significantly reduce costs and improve efficiency. In addition, support for manufacturing SMEs to implement market standards and access

accredited testing laboratories is necessary for global competitiveness, and a supportive national regulatory framework is needed to encourage business growth and innovation within the SME sector.

Conclusion

In conclusion, the study revealed that manufacturing SMEs already anchor Ghana's inclusive growth, but their potential remains underexploited and vulnerable without coherent, competition-oriented policy reform. A comprehensive agenda that enforces fair competition, upgrades infrastructure and energy reliability, expands targeted financing and business development services, and supports the adoption of modern technologies and quality standards is essential to convert SME dominance in employment and firm counts into sustained productivity growth and structural transformation. If such measures are effectively implemented, manufacturing SMEs can move from merely absorbing labour to leading Ghana's progression toward a more resilient, diversified, and innovation-driven industrial economy.

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An Empirical Analysis of Consumer Preferences For Salty Snacks

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Abstract: The consumption of salty snacks has a long tradition in Hungary; however, salty wafers represent a traditional product category whose marketing visibility and innovation dynamics appear weaker than those of several competing pre-packaged salty snack categories. The aim of this study is to examine consumer preferences for salty snacks, with particular emphasis on cheese wafers and the mini cheese wafer variant, and to identify factors that may influence awareness, purchase intention, packaging preference, and openness to innovation.

The research was conducted through a questionnaire survey involving 1,010 respondents in Heves County. The analysis examined purchase intention, consumption habits, media-related information sources, price/value sensitivity, and attitudes toward newly introduced salty wafer products across three analytical age groups. Respondents under 18 years of age were included only with parental or guardian consent, and the responses were processed anonymously and in aggregated form.

The findings show that most respondents are familiar with and have a positive attitude toward salty wafers, while awareness of the mini cheese wafer remains considerably lower. Among respondents previously unfamiliar with the mini variant, 91% indicated willingness to try the product after it was shown to them. The results suggest that technological modernisation, product innovation, aroma-protective packaging, broader retail availability, and more conscious marketing communication may strengthen the market position of salty wafers. Because the sample is geographically limited and non-probabilistic, the findings should be interpreted as indicative rather than nationally representative.

Keywords: purchase intention, food consumption, sociodemographic factors.

1 Introduction

The baking and pasta industry is one of the most important sectors of the food industry; the first factory unit in Hungary was established in 1859 under the name First Hungarian Steam Pasta Factory [1]. Enormous technological development has taken place, as a result of which high-quality pre-packaged food products are available in today's world. It is of considerable importance for the environment, sustainability, and society that innovation and development reach production lines as quickly as possible so that consumers receive the highest possible quality at the lowest possible prices. Salty biscuits, potato crisps, and salty wafers are highly popular, easily accessible, and ready for immediate consumption.

In Hungary, snacks with cheese, onion-and-sour-cream, and paprika flavours are the most popular. Sales are highest in the second, third, and fourth quarters [2], and many snack producers also market larger packages during major world sporting events, thereby maximising profit. During the past two decades, the popularity of potato crisps has increased steadily at the expense of other salty snacks; nevertheless, wafers, as traditional Hungarian savoury baked products, have managed to remain on the market. Some producers have recognised that, in order to expand further, salty wafers need to be broadened and their flavour profile updated in line with current trends and consumer needs, similarly to the direction observed in the potato crisp segment. Through cooperation among producers, processors, traders, and civil organisations, it is necessary to establish an appropriate product base, supported by well-communicated distribution that reflects local characteristics, with direct forms being preferred [3].

Starting up food production is a multifaceted task and, from the 2020s onward, requires a novel organisational approach in an economic and social environment that is changing ever more rapidly and markedly. In previous decades, the market followed a more predictable rhythm, but the arrival of COVID-19 and the sudden rise in energy prices introduced a new perspective. According to Kürthy and co-authors [4], labour efficiency in the Hungarian food industry lags behind that observed in the European Union. This can be explained by the relatively low domestic labour costs, which reduce firms' willingness to move toward technological development because of the high prices of such investments. Faster and more accurate problem solving is now required than ever before from company management, regardless of hierarchical level, and this places increasing emphasis on the competence and expertise of decision-makers.

The research problem was therefore formulated on the basis of the literature on consumer-driven food product development, digital transformation in the agri-food sector, functional foods, packaging cues, and social media food marketing [5]-[15]. These sources indicate that product development is more successful when it is aligned with consumer needs, perceived product benefits, packaging-related quality signals, and the communication channels used by the target group. The present

article consequently focuses on a narrowly defined case, the mini cheese wafer, and examines whether a traditional but less dynamically marketed product can be repositioned through innovation, packaging development, and targeted marketing communication.

2 Literature review

Hungarian food industry enterprises can keep pace with competitors only if they are able to adapt to technological and market changes [10], [16]. In the case of salty wafers, modernisation may involve not only production technology but also product policy, flavour development, packaging, and communication. Previous studies on consumer-driven product development emphasize that successful food innovation should start from consumer needs and preferences [5]. This is especially relevant for traditional products that are widely known but receive less systematic marketing support than competing snack categories.

The literature on functional foods and health-related food choices also supports the examination of innovation potential. Consumers who perceive a product as healthier or more beneficial tend to evaluate it more positively and may be willing to pay a price premium [7], [8], [11], [12]. Packaging is similarly relevant because extrinsic product attributes, such as colour, readability, and visual quality, can influence perceived healthiness and product quality at the point of purchase [9]. These findings justify the inclusion of packaging added value and price/value sensitivity among the research objectives.

Packaging, product information, and marketing communication may exert a measurable influence on consumer perception and choice even under experimental conditions. In their experimental study, Becker et al. demonstrated that the formal and visual characteristics of packaging can affect consumers' impressions of taste intensity and product evaluation [17]. This is relevant in the case of salty wafers because modern aroma- and quality-preserving packaging can be interpreted not only as a technological element but also as a marketing tool that influences perceived product quality.

Pinto et al. examined the role of packaging and health-related claims in the case of snack bars. Their results indicate that health-related information and product-benefit claims displayed on packaging can influence consumer perception and sensory acceptability [18]. This supports the view that, when developing salty wafers, not only flavour variations but also the messages communicated through packaging should be examined as market-relevant factors. These may include preservative-free production, freshness preservation, and the communication of modern packaging technology.

Regarding the reach of younger consumers, the examination of digital and social-media-based food marketing is particularly relevant. Coates et al. investigated, in a randomised experiment, the effect of food marketing communicated by social media influencers on children's food choices and consumption [19]. The online randomised study by Bragg et al. also showed that food marketing on Instagram may influence adolescents' advertising perception and food preferences [13]. These studies directly justify the inclusion of social media as a key research dimension when examining the market development of salty wafers, particularly the mini cheese wafer.

The effects of front-of-package information and labels were analysed by Grummon et al. in a large-scale randomised clinical trial involving hypothetical beverage and snack selection tasks. Their findings showed that interpretive front-of-package labelling systems reduced the energy content of selected snacks and beverages compared with the control condition [20]. In the case of snack products, packaging therefore fulfils not only an aesthetic or logistical function but may also play a significant role in guiding purchase decisions and shaping perceptions of product healthiness.

The importance of visual elements in snack packaging was also confirmed by Wang et al., who examined the impact of snack food packaging design characteristics on consumer purchase decisions. According to their research, colour, shape, imagery, line design, and typography are key elements of snack packaging that may influence purchasing decisions [21]. This is important for the present research because, when evaluating the market potential of the mini cheese wafer, the development of visual appearance and packaging communication represents an indispensable practical direction alongside product development.

Marketing communication is another important dimension. Prior research shows that food and beverage brands can reach young consumers effectively through social media, and that platform-specific marketing may influence advertisement perception and food preferences [13], [14]. In addition, interactive and informative social media marketing can affect purchase decisions through brand-related mechanisms [15]. For this reason, the study examines not only product awareness and purchase intention but also the media channels through which respondents encounter cheese wafer-related communication.

Secondary data are also used to frame the market context. KSH demographic data support the interpretation of the 18-60 age group as an economically important consumer segment [2], while FMCG retail-chain turnover data provide background for evaluating retail availability and distribution-related recommendations [22]. The research objectives were derived from this combined literature and secondary-data background rather than from personal impressions.

3 Materials and methods

A quantitative questionnaire survey was conducted in the first half of 2023 with the assistance of 14 interviewers and the involvement of 1,010 respondents. The study focused primarily on the two-centimetre-diameter mini cheese wafer and secondarily on the regular-sized cheese wafer with a diameter of eight to ten centimetres. A self-designed questionnaire was used, and the responses were analysed with descriptive statistics and selected inferential statistical procedures. In terms of information acquisition, the study relied on primary market research [23].

The fieldwork was carried out at eight retail units selling basic food products within food retail shopping centres in Heves County. The sampling procedure was a non-probability, face-to-face intercept survey; therefore, the findings describe the surveyed respondents and should not be treated as representative of the entire Hungarian population.

The research objectives were defined on the basis of the literature review and the secondary-data background presented above. The study examined the market position and perception of the mini cheese wafer because salty wafers are a traditional, well-known product category, while their innovation, packaging development, retail presence, and communication appear less intensive than in several competing salty snack segments. The questionnaire was intentionally kept short and easy to understand in order to support accurate data collection in a retail environment.

Participants were grouped into three analytical age categories: respondents under 18 years, respondents aged 18-60 years, and respondents aged 61 years and above. Respondents under 18 years of age participated only with parental or guardian consent; participation was voluntary, the questionnaire was anonymous, and results were processed only in aggregated form. Age and gender were recorded as control variables for sample description and subgroup interpretation, but the composition of the sample was not treated as an independent research objective. The results were analysed using The R Project for Statistical Computing software.

3.1 Research objectives and questionnaire structure

- 1 Comparison of awareness of the regular-sized cheese wafer and the mini wafer
- 2 Identification of purchase willingness and purchase frequency related to the mini cheese wafer
- 3 Assessment of the role of different marketing and media channels in cheese wafer-related communication
- 4 Examination of openness to flavour and product innovation across age groups
- 5 Examination of price/value sensitivity by age group

6 Examination of consumer preference for the added value of aroma-protective packaging

Age and gender were retained only as control variables for describing the sample and interpreting subgroup differences; they are not independent research objectives.

Research objective / control variable	Questionnaire item
Comparison of awareness of the regular-sized cheese wafer and the mini cheese wafer	1. Do you know the cheese wafer product? (Yes/No); 2. Do you know the mini cheese wafer product? (Yes/No)
Identification of purchase willingness and purchase frequency related to the mini cheese wafer	3. Compared with the regular-sized wafer, would you purchase the mini wafer? (for those who answered no to Q2) (Yes/No); 4. How often do you purchase mini cheese wafers? (for those who answered yes to Q2) (Weekly/Monthly)
Assessment of the role of different marketing and media channels in cheese wafer-related communication	5. Have you ever encountered an advertisement for cheese wafers in the media? (TV; Radio; Print media; Social media; Do not know/No)
Examination of openness to flavour and product innovation across age groups	6. Would you buy a mini wafer with flavours different from the traditional Hungarian flavour profile? (Yes/No)
Examination of price/value sensitivity by age group	7. Instead of the 100-gram package, would you choose a 500-gram package if the consumer price were more favourable? (Yes/No)
Examination of consumer preference for the added value of aroma-protective packaging	8. Do you prefer transparent packaging or aroma-protective packaging? (Transparent packaging; aroma-protective packaging)
Control variables used only for sample description and subgroup interpretation (not a research objective)	9. What is your gender? (Female/Male); 10. What is your age group? (Under 18 years; 18-60 years; 61 years and above)

Table 1
Research objectives, questionnaire items and control variables
Source: author's own compilation

4 Analysis of the research results

This section presents the results of the primary research using descriptive statistics, cross-tabulations, selected statistical tests, and The R Project for Statistical Computing software.

The demographic characteristics of the sample are presented first only as sample-description variables; the subsequent subsections analyse the substantive research questions and formulate market-oriented interpretations.

4.1 Demographic characteristics

The demographic structure of the sample is presented only to describe the database and to support the interpretation of age- and gender-specific results. It is not an independent objective of the study. Of the 1,010 respondents, 71% were women. The proportion of female respondents was 65% among respondents under 18 years of age, 73% in the 18-60 age group, and 72% in the 61 years and above age group. The weighted mean of female participation was 0.7031 and the weighted standard deviation was 0.034, indicating relatively stable gender proportions across the age groups.

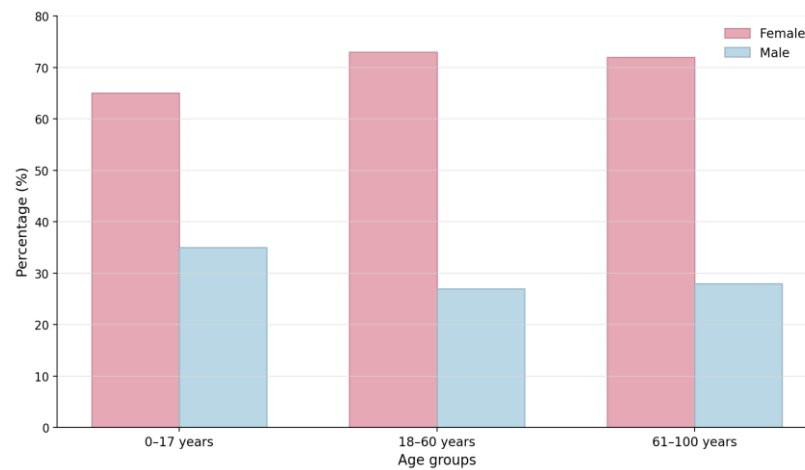


Figure 1

Demographic characteristics of the research participants by gender.

Source: author's own compilation (2024), N = 1,010

4.2 Assessment of the ratio between awareness of the cheese wafer and the mini cheese wafer

Responses to the question on awareness of the regular-sized cheese wafer showed that 96.5% of respondents answered yes. This indicates that the product has a very high level of consumer familiarity in the surveyed market. In marketing terms, high awareness represents a favourable starting point, but it does not automatically ensure purchase frequency or market growth; market growth also depends on availability, perceived value, packaging, and communication [5], [24].

Awareness of the mini product variant was considerably lower: 43% of respondents indicated that they were familiar with mini cheese wafers. The gap between the 96.5% awareness of the regular-sized product and the 43% awareness of the mini variant suggests that the mini wafer has substantial market-development potential, especially if supported by improved retail availability and more targeted communication. The difference in awareness between the two product sizes is shown in Figure 2.

When awareness is treated as a binary variable, where 1 represents awareness and 0 represents lack of awareness, the estimated standard deviation for the regular-sized wafer is $\sigma \approx 0.184$, while the estimated standard deviation for the mini wafer is $\sigma \approx 0.495$. This indicates that awareness of the mini variant is much more heterogeneous in the sample, which supports the need for further marketing communication and distribution development.

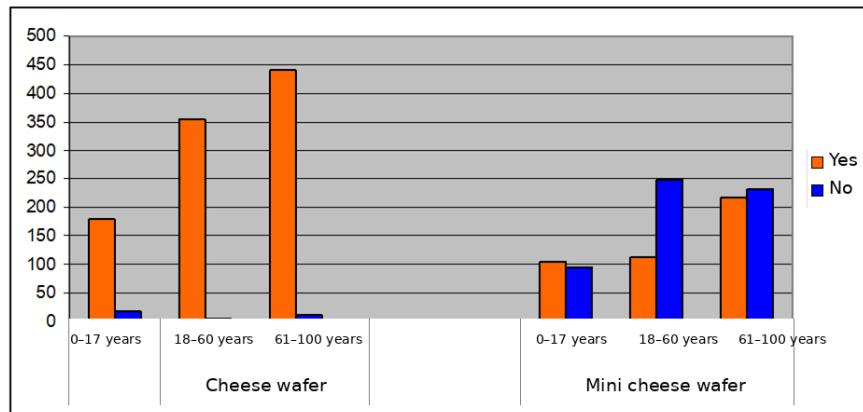


Figure 2
Difference in awareness between the regular-sized and the mini cheese wafer.
Source: author's own compilation (2024), N = 1,010

4.3 Examination of purchase frequency and purchase willingness regarding the mini cheese wafer

The proportion of respondents purchasing the mini cheese wafer weekly was 29%. This result indicates that awareness alone is not sufficient to create routine purchasing behaviour. Although the mini wafer was known by 43% of respondents, its purchase frequency remained relatively low, suggesting that communication, availability, and repeated consumer contact may be necessary to convert awareness into regular purchasing.

Respondents who were not familiar with the mini cheese wafer (N = 575; 57% of the full sample) were asked whether they would try the mini wafer instead of the regular-sized product in the future. During this question, the interviewers physically showed the respondents the mini cheese wafer package. Willingness to purchase the previously unfamiliar product reached 91%, indicating strong potential for trial. This result should nevertheless be interpreted with caution because direct product presentation and face-to-face interaction may increase positive responses.

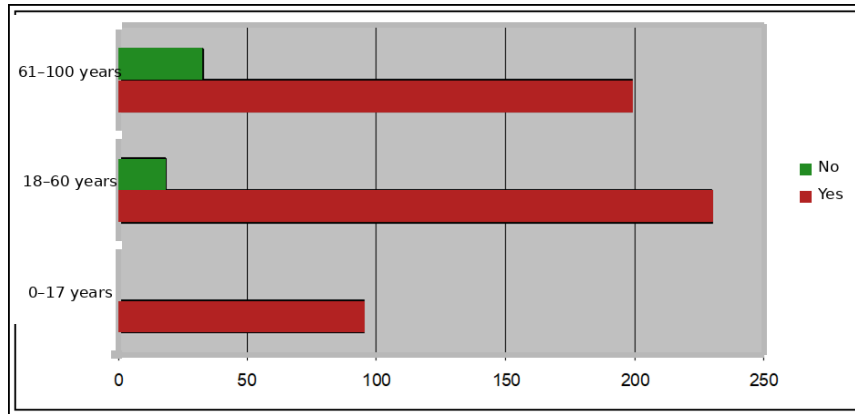


Figure 3
Distribution of purchase willingness regarding the mini cheese wafer.
Source: author's own compilation (2024), N = 575

4.4 Share of different marketing activities in the media

Television and radio advertisements were mainly reported by adult and older respondents, while the low value measured among younger respondents indicates that these channels have limited relevance for reaching the youngest consumer segment. Print media responses were interpreted cautiously, because respondents often associated this category with retail promotional leaflets rather than with traditional newspaper or magazine advertising. The low social-media value in the responses is important because younger consumers are generally more reachable through digital platforms than through traditional media.

For the first time in the 18-year history of Facebook, the number of users did not increase in the first quarter of 2023; instead, it declined. Instagram also showed a decline during this period, with 500,000 fewer users than in 2022. In 2023, the number of TikTok users exceeded one billion, and this platform appears to offer the greatest potential for younger age groups, who open the application on a daily basis at a rate of 82% [25]. According to Eurostat (2017), Hungarian internet users, with a usage rate of 83%, are the most intensive users of social media platforms in Europe [26].

International literature also confirms that food and beverage brands reach underage target groups particularly effectively through social media platforms, and that platform-specific presence can positively influence perceptions of advertisements as well as product preferences [13], [14]. In addition, the interactivity, relevance, and informativeness of social media marketing can also positively affect purchase decisions; therefore, the role of social media is of outstanding importance in reaching young target groups [15].

The proportion of 61.7% in the 'do not know/no' category indicates limited perceived visibility of cheese wafer promotion. Industry consultations suggested that some producers advertise through television, radio, print media, or Facebook, while Instagram and TikTok presence is more limited. This finding is consistent with the literature indicating that social media has a strong role in reaching young consumers [13]-[15]. The frequency of advertisement appearances across media platforms is shown in Figure 4.

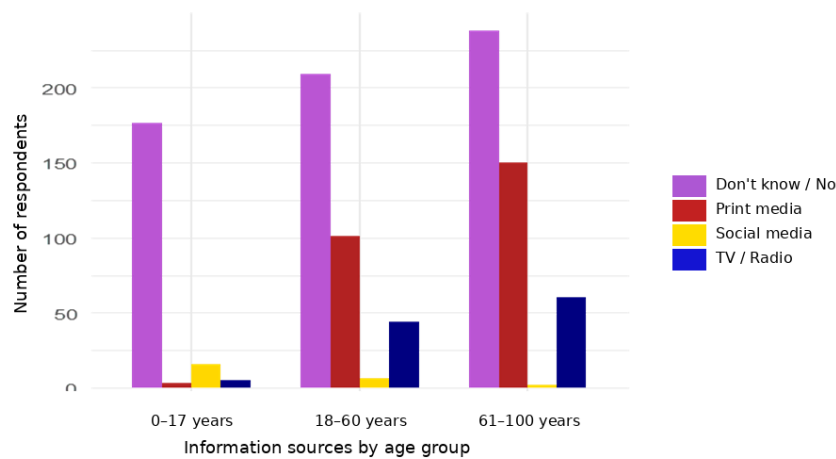


Figure 4
Frequency of advertisement appearances across media platforms.
Source: author's own compilation (2024), N = 1,010

4.5 Importance of innovation in different age groups

Openness to new flavours was strongest among younger respondents; the 91.5% value measured in this group provides a favourable basis for product innovation. The rise of potato crisps and the diversification of their flavour profiles suggest that flavour innovation may also support the renewal of traditional salty wafers. At the time of the study, the domestic salty wafer market was dominated by traditional salted, cheese, and caraway versions; therefore, the introduction of Asian, Mexican, Indian, or other contemporary flavour profiles could be tested first among younger consumers through targeted social media communication. The proportion of respondents open to novelty is shown in the revised Figure 5.

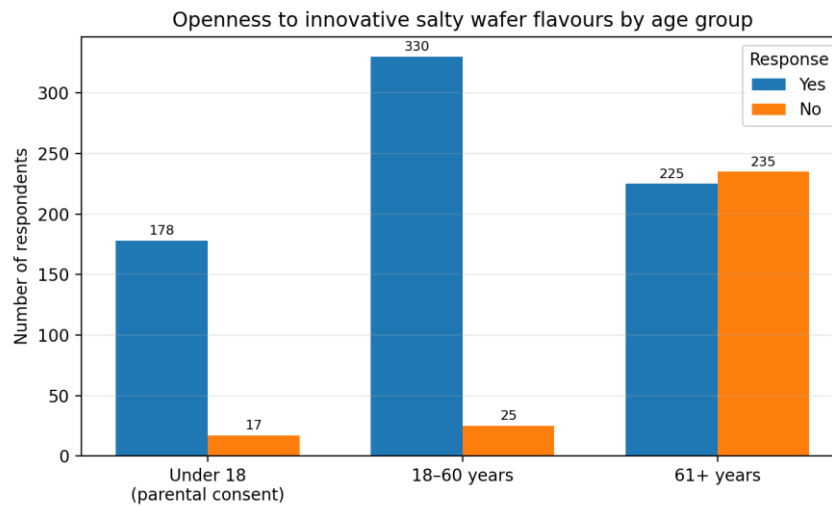


Figure 5.

Openness to innovative salty wafer flavours by age group.

Source: author's own compilation (2024), N = 1,010

4.6 Examination of the importance of the price/value ratio by age group

Price/value sensitivity increased with age in the sample. A more favourable consumer price for the 500-gram package was important to 45.0% of respondents under 18 years of age (Yes = 81; No = 99), 88.6% of respondents aged 18-60 years (Yes = 310; No = 40), and 95.5% of respondents aged 61 years and above (Yes = 420; No = 20). The chi-square test indicated a statistically significant association between age group and response distribution ($p < 0.001$). These results suggest that smaller packages may be more appropriate for launching innovative flavours among younger consumers, while larger value packs may be more attractive for older, price-sensitive consumers. The price/value ratio by age group is presented in the revised Figure 6.

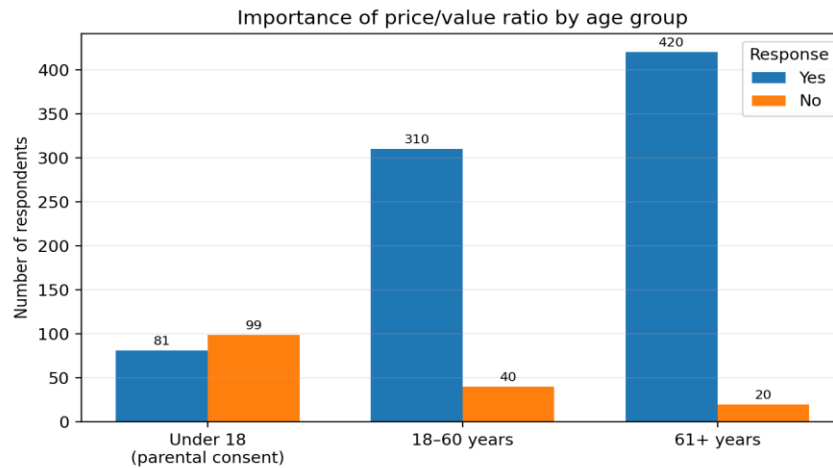


Figure 6.

Importance of price/value ratio by age group.

Source: author's own compilation (2024), N = 1,010

4.7 Examination of the importance of the added value of packaging

The interviewers had products with both packaging types available so that respondents could form their opinions on the basis of direct product presentation. Among respondents under 18 years of age, 98% chose aroma-protective packaging, mainly because of its modern visual appearance and stronger graphic effect. In the 18-60 age group, 75% considered it important that aroma-protective technology and the use of food gases may support preservative-free production. In the 61 years and above group, transparent packaging remained more acceptable: 69% preferred or accepted the older transparent solution, which may be linked to price expectations and familiarity with traditional packaging. The results suggest that aroma-protective packaging is particularly suitable for new flavours and for younger or middle-aged target groups, while price-sensitive older consumers may require clear communication of the added value of the more modern packaging.

Packaging preferences are shown in Figure 7.

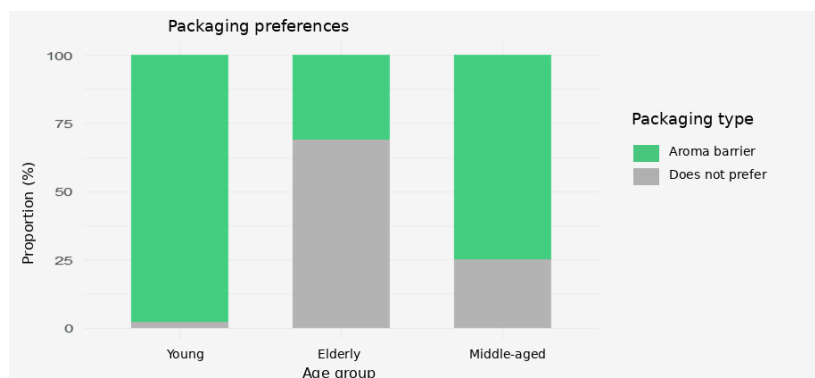


Figure 7

Proportion of packaging preferences.

Source: author's own compilation (2024), N = 1,010

Conclusions and recommendations

Based on the high awareness of the regular-sized cheese wafer, salty wafers provide a market base on which product and marketing development can be built. At the same time, the much lower awareness of the mini cheese wafer shows that the category has not yet fully exploited its market potential. The findings support the need for modernisation in product policy, packaging, distribution, and communication, which is consistent with the literature on food-industry innovation, consumer-driven product development, and packaging-related quality perception [5], [7]-[12], [16].

The results suggest that product innovation may help reduce the competitive disadvantage of salty wafers compared with potato crisps and savoury biscuits. New flavour profiles, smaller innovation-oriented packages, and social media communication may be especially relevant for younger consumers, while larger value packs and clear price/value communication may be more effective for older consumers.

The study also highlights the practical importance of aroma-protective packaging. This packaging type can strengthen perceived product quality, support longer shelf life, and make preservative-free production easier to communicate. The preference patterns observed in the sample indicate that packaging development should be linked to age-specific positioning rather than treated as a purely technological decision.

From a marketing-management perspective, the four most important development areas are product policy, pricing policy, distribution policy, and communication policy. The 18-60 age group is especially important because KSH data indicate that this age category represents a large, economically active consumer base in Hungary

[2]. Retail-chain turnover data [22] also underline the need to increase availability beyond the currently limited retail presence. Broader distribution in FMCG chains could support repeat purchase, while smaller shops and markets may remain important among older consumers who value personal contact and habit-based purchasing.

Standard deviation analysis makes it possible to determine how strongly company turnover figures are dispersed around the mean: if the standard deviation is smaller, the firms are of a similar order of magnitude; if the standard deviation is larger, the differences are greater. Average turnover was HUF 896 billion and the standard deviation was HUF 307.9 billion. Lidl is significantly above the average, lying more than +1 standard deviation above it; Aldi and CBA are below the average, COOP and Tesco are around the average, while SPAR performs slightly above the average to a negligible extent.



Figure 8
Business ranking of FMCG retail chains in 2024.
Source: author's own compilation, 2024

Figure 8 provides background information on the relative turnover of selected FMCG retail chains and supports the interpretation of potential distribution channels. In the surveyed retail context, mini wafer products were found to be available only in Coop Zrt. stores; therefore, broader retail presence should be considered a primary market-development task. The older age group constitutes a stable consumer base: awareness of the cheese wafer is 97.5% among them, while awareness of the mini cheese wafer is 48%. This group is also characterized by a preference for markets and smaller shops, where personal contact and familiarity may support repeat purchasing.

Limitations of the study

The study has several limitations that should be considered when interpreting the results. First, the sample was collected in Heves County through a non-probability, face-to-face intercept survey at retail units; consequently, the findings cannot be generalized to the entire Hungarian population without further research. Second, the sample contains a higher proportion of women, which may influence the interpretation of purchase-related results. Third, respondents under 18 years of age were included only with parental or guardian consent, and their answers should be interpreted with additional caution because minors may differ from adult consumers in purchasing autonomy and decision-making responsibility.

Further limitations arise from the use of a self-designed questionnaire and from the fact that the study measured stated purchase intention rather than actual sales behaviour. In addition, the physical presentation of the mini cheese wafer package during the interview may have increased trial willingness through the effect of direct product contact and interviewer interaction. Finally, the study focuses on one specific traditional salty snack product and only partially covers the wider salty snack category; therefore, future research should examine additional product types, regions, sales data, and longitudinal changes in consumer behaviour.

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Online Platform Data for Tourism Research in Northern Albania: A Comparative Analysis of Booking.com and TripAdvisor

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Abstract: The increasing digitalization of the tourism sector has expanded the availability of data from online travel platforms, creating new opportunities for tourism research, particularly in destinations where traditional statistics are limited. Building on existing literature that highlights the growing role of user-generated content and platform-based data, this study examines the potential of online platforms as sources of tourism insights. A comparative analysis is conducted using two datasets collected from Booking.com and TripAdvisor, focusing on accommodation listings in Northern Albania. Data preprocessing and analysis were performed using Python, enabling the cleaning, matching, and normalization of accommodation units across platforms. The study applies descriptive statistics and cross-platform comparison to explore differences in rating distribution, review volume, and how accommodation performance is represented. The findings indicate that while both platforms reflect similar overall trends, significant differences emerge in the variability and interpretation of key indicators. These differences are linked to platform-specific characteristics, including user participation and evaluation mechanisms. The study highlights the importance of interpreting online platform data and demonstrates the value of comparative approaches for tourism research in emerging destinations.

Keywords: Online platform data; Booking.com; TripAdvisor; Comparative analysis; Northern Albania

1 Introduction

The increasing digitalization of the tourism sector has transformed the way travelers search for, evaluate, and select accommodation services. Platforms such as Booking.com and TripAdvisor have become central sources of information, providing access to user-generated content, including ratings, reviews, and descriptive details about accommodation units. Beyond their role as information channels, these platforms have also emerged as key sources of digital data, generating large volumes of information that can complement traditional tourism statistics and support data-driven analysis [1].

In addition to their informational role, online platforms have gained importance as valuable data sources for tourism research. The availability of platform-based data offers new opportunities to analyze tourism performance, particularly in destinations where traditional statistical data may be limited, aggregated, or delayed [2]. In the context of Northern Albania, official tourism statistics often do not fully capture patterns of accommodation performance, user engagement, and digital visibility. As a result, data derived from online platforms can provide complementary insights into the dynamics of the tourism sector [3].

However, online platform data are not neutral. Differences in platform structure, user behavior, review verification systems, and evaluation mechanisms can influence how information is generated and represented. Booking.com, for example, collects reviews only from verified users who have completed a stay, while TripAdvisor allows broader participation. These differences may affect rating consistency, review volume, and the representation of accommodation performance [4]. Consequently, data obtained from different platforms may not be directly comparable.

Existing research highlights the importance of analyzing multiple platforms to better understand these differences. While many studies have relied on a single data source, comparative approaches allow researchers to identify inconsistencies, biases, and platform-specific patterns in online tourism data [5]. This is particularly important when platform-based indicators are used to support tourism analysis, decision-making, or policy development.

In this context, the present study aims to examine the potential of online platform data for tourism research through a comparative analysis of Booking.com and TripAdvisor accommodation listings in Northern Albania. The study focuses on accommodation units present on both platforms and compares key indicators, including rating scores, review volume, and rating distribution patterns. Using

Python for data preprocessing, matching, and analysis, the study applies descriptive statistics and visual exploration to identify similarities and differences in how tourism performance is represented across platforms [6].

The findings of this study provide insights into the extent to which online platforms reflect consistent or divergent representations of accommodation performance. By highlighting differences in user engagement, rating variability, and platform-based evaluation systems, the study contributes to a better understanding of the strengths and limitations of online platform data. The research emphasizes the importance of interpreting such data when used for tourism analysis, particularly in emerging destinations such as Northern Albania.

2 Literature review

The development of Information and Communication Technologies (ICTs) has fundamentally transformed the tourism industry, giving rise to the concept of eTourism. ICTs have reshaped business models, enabling more efficient distribution systems, improving service delivery, and facilitating direct interaction between tourism stakeholders and consumers [7]. This transformation has accelerated with the emergence of digital platforms, which now act as central intermediaries in the tourism ecosystem.

Digital platforms such as Booking.com and TripAdvisor function as multi-sided marketplaces that connect service providers and consumers while reducing search costs and increasing market transparency [8]. These platforms enable tourists to access, evaluate, and compare accommodation options easily, thus influencing travel decision-making processes. The integration of user-generated content (UGC) has further strengthened their role, making them key sources of tourism-related information.

Online reviews, as a form of electronic word-of-mouth (eWOM), play a crucial role in reducing uncertainty associated with tourism products, which are inherently intangible and experience-based. Travelers rely on peer-generated content to evaluate service quality and make informed decisions. Research shows that online reviews significantly influence booking behavior and contribute to building trust and reducing perceived risk [9]. Moreover, online reviews not only influence consumers but also provide valuable feedback to service providers, helping them improve performance and competitiveness [10].

Despite their importance, online review platforms are not homogeneous. Significant differences exist between platforms such as TripAdvisor and Booking.com in terms of data structure, user behavior, and evaluation mechanisms. Booking.com relies on verified reviews from actual customers, whereas TripAdvisor allows broader participation, including anonymous contributions. These structural differences

influence rating patterns, review content, and data reliability, leading to variations in how accommodation performance is represented [11].

Beyond structural differences, platforms also vary in how they shape user perceptions and represent accommodation experiences. While Booking.com provides a more standardized evaluation framework, TripAdvisor tends to reflect a wider range of subjective experiences. As a result, the same accommodation unit may be perceived differently depending on the platform, highlighting the importance of examining multiple sources when analyzing tourism data [12].

Research comparing these platforms highlights important differences. For instance, the relationship between the number of reviews and rating scores differs significantly between platforms. A positive relationship between review volume and scores is often observed on TripAdvisor, while this relationship is weaker or absent on Booking.com [13]. This suggests that platform dynamics, such as user participation and rating systems, directly affect how aggregated indicators are formed.

The increasing availability of digital data has further expanded opportunities for tourism research. Online platforms generate vast amounts of real-time data, offering more granular and timely insights compared to traditional statistics. Big data sources, including social media and online booking platforms, provide new opportunities for measuring tourism flows, performance, and consumer behavior, although they also introduce challenges related to data quality and bias [1].

In this context, web scraping has become an important methodological tool for extracting and analyzing large-scale tourism data. It allows researchers to collect structured and unstructured data from online platforms efficiently, enabling deeper insights into customer behavior, preferences, and market dynamics [14]. Such approaches are particularly valuable in regions where official tourism statistics are limited or delayed.

In the case of Albania, the use of online platform data presents a significant opportunity for tourism analysis. Studies have demonstrated that data from platforms such as TripAdvisor can be used to develop indicators of tourism development, offering insights into accommodation quality, customer satisfaction, and market trends [3]. This is particularly relevant for emerging destinations, where traditional data sources may not fully capture tourism dynamics.

The literature demonstrates that online travel platforms are not neutral data sources but are shaped by platform-specific characteristics, including verification systems, user behavior, and evaluation mechanisms. These differences influence how tourism performance is represented and interpreted. A comparative approach is necessary to better understand the extent to which platform-based data provide consistent and reliable insights, particularly in emerging destinations such as Northern Albania.

3 Methodology

This study applies an exploratory, data-driven methodology to compare how two major online travel platforms, Booking.com and TripAdvisor, represent accommodation performance in Northern Albania. The methodological design follows prior comparative platform studies, which emphasize the need to analyze the same accommodation units across different online review systems in order to identify structural differences in rating behavior, review volume, and platform-based representation.

The study is based on two datasets collected from Booking.com and TripAdvisor. The datasets include accommodation listings located in Northern Albania and contain key variables such as accommodation name, rating score, number of reviews, and descriptive attributes related to each accommodation unit. Online platform data are used as an alternative and complementary source of tourism information, particularly in contexts where official statistics may be limited in granularity, frequency, or detail [15].

Data preprocessing and analysis were conducted using Python. The preprocessing phase included cleaning the datasets, standardizing accommodation names, checking for missing or inconsistent values, and preparing the variables for comparison. This follows the logic of exploratory data analysis, where Python is used to inspect datasets, identify missing values, clean incorrect records, examine variable distributions, and visualize relationships between variables [6][14].

To identify accommodation units present on both platforms we applied a matching procedure. Since hotel names may appear with small variations across platforms, the matching process involved standardizing names, removing unnecessary characters, checking spelling differences, and manually verifying uncertain matches. Only matched accommodation units were retained for the final comparative analysis. This step was necessary because the objective of the study is not to compare the platforms in general, but to examine how the same accommodation units are represented differently across Booking.com and TripAdvisor.

To ensure comparability, TripAdvisor ratings were transformed to a common 0–10 scale, aligning them with the rating scale used by Booking.com. This normalization step is important because previous studies show that differences in platform rating scales can influence the interpretation of hotel performance across Booking.com and TripAdvisor [11]. Review counts were retained as reported on each platform, as they represent the level of user engagement and digital visibility generated by each accommodation unit.

The analytical approach combines descriptive statistics, visual exploration, and cross-platform comparison. First, review counts were aggregated by platform to compare the level of user engagement. Second, rating distributions were examined

to assess differences in variability and concentration across platforms. Third, the relationship between Booking.com and TripAdvisor ratings was analyzed using a scatter plot with a fitted trend line, allowing the study to identify whether accommodations rated highly on one platform also tend to receive high ratings on the other. This approach is consistent with comparative platform analytics, where multiple online review platforms are examined to understand whether they provide consistent or divergent representations of hotel performance.

This study is exploratory in nature rather than predictive. It aims to identify patterns, differences, and platform-specific tendencies, without seeking to establish generalizable causal relationships. This is appropriate because online platform data may be affected by platform design, user behavior, data availability, and self-selection bias. The findings are interpreted cautiously as evidence of cross-platform differences in the representation of accommodation performance in Northern Albania.

4 Results

4.1 Review volume across platforms

The comparative analysis of review counts reveals a clear difference in user engagement between the two platforms. Booking.com records 6,449 reviews compared to 1,092 on TripAdvisor, indicating a substantially higher level of user participation. This difference suggests that review volume varies considerably across platforms and should be interpreted with caution in comparative analyses.

4.2 Rating distribution across platforms

The distribution of ratings across platforms reveals notable differences in variability and consistency. As shown in Figure 1, ratings on Booking.com are relatively concentrated within a narrow range, indicating a more stable and consistent evaluation pattern among users. The red line represents the mean rating for each platform, highlighting the difference in central tendency between Booking.com and TripAdvisor. Most ratings are clustered at higher values, suggesting limited dispersion.

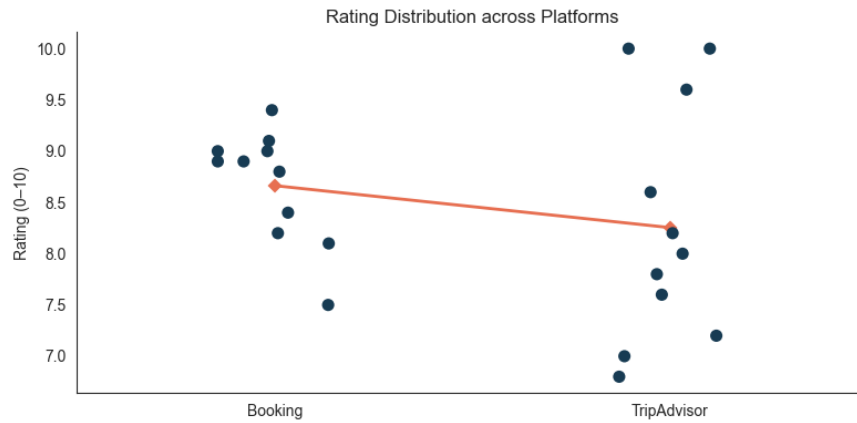


Figure 1
Distribution of accommodation ratings across Booking.com and TripAdvisor

In contrast, TripAdvisor ratings display a wider spread. This variability indicates more diverse user evaluations. The observed differences suggest that the two platforms capture user sentiment in distinct ways, likely influenced by differences in review systems and user behaviour.

4.3 Relationship between ratings across platforms

The relationship between ratings on Booking.com and TripAdvisor is presented in Figure 2 through a scatter plot. The results indicate a positive association between ratings across the two platforms, suggesting that accommodations with higher ratings on one platform tend to receive higher ratings on the other. The red line represents the regression trend, showing the overall relationship between the two variables. However, the dispersion of data points around the trend line reveals that this relationship is not perfectly aligned. Several accommodations exhibit noticeable differences in ratings between platforms, indicating that the same unit may be evaluated differently depending on the platform. This variability highlights the presence of platform-specific factors influencing user evaluations.

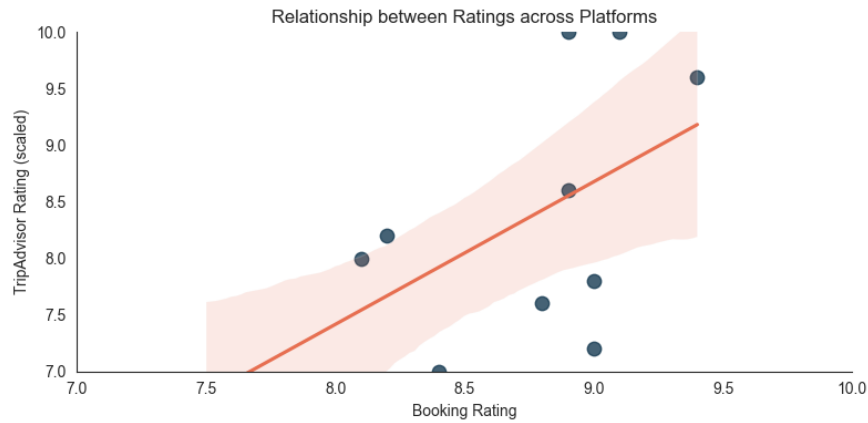


Figure 2
Relationship between accommodation ratings on Booking.com and TripAdvisor

While a general trend of consistency is observed, the differences at the individual level suggest that platform-based ratings should not be considered directly interchangeable.

5 Discussion

The findings of this study confirm that online travel platforms differ not only in structure but also in how they represent tourism performance. The comparative analysis of Booking.com and TripAdvisor data reveals both similarities and differences in key indicators, highlighting the need for careful interpretation of platform-based information.

A key result of the analysis is the difference in review volume between the two platforms, with Booking.com showing much higher user engagement. This aligns with prior research suggesting that review volume is associated with the stability and representation of ratings across online platforms [13]. A larger number of reviews increases the influence of online information and reduces uncertainty in consumer decision-making [16]. However, the imbalance in review counts suggests that the two platforms operate under different engagement dynamics, which may affect data representativeness.

The analysis of rating distribution reveals that Booking.com ratings are more concentrated, while TripAdvisor ratings display greater variability. This reflects structural differences between platforms, particularly in their review verification mechanisms. Booking.com restricts reviews to verified users who have completed

a stay, leading to more stable and consistent rating patterns. In contrast, TripAdvisor allows broader participation, resulting in more diverse and potentially more volatile evaluations [4]. The wider dispersion of TripAdvisor ratings observed in this study supports this interpretation and confirms that platform design plays a crucial role in shaping user evaluations. This is consistent with previous comparative studies on Booking.com and TripAdvisor, which show that differences in platform structure and user participation can lead to divergent representations of accommodation performance [17].

The relationship between ratings across platforms is positive but not identical. While accommodations with higher ratings on one platform tend to receive higher ratings on the other, deviations are observed. This indicates that ratings are influenced by platform-specific factors and should not be treated as directly interchangeable. This finding is in line with research suggesting that rating behavior is not always symmetric and may vary depending on context and platform characteristics [18].

These differences can be explained by how platforms influence consumer perception. Although both Booking.com and TripAdvisor rely on user-generated content, they present accommodation experiences in different ways. TripAdvisor reflects a broader range of subjective experiences, while Booking.com provides a more structured and standardized evaluation framework. The results of this study support this perspective, as the greater variability in TripAdvisor ratings suggests a wider range of user opinions and experiences [12].

The results show that online travel platforms should not be treated as directly equivalent data sources. Differences in user engagement, rating patterns, and platform mechanisms affect how tourism performance is represented. These findings are particularly relevant for emerging destinations such as Northern Albania, where online platforms can serve as key sources of tourism insights [3]. Researchers and practitioners should therefore consider platform-specific characteristics when analyzing and comparing tourism performance indicators.

Conclusions

This study examined the use of online travel platforms as sources of tourism data through a comparative analysis of Booking.com and TripAdvisor in Northern Albania. The results show that, while both platforms reflect similar general trends, they differ in review volume, rating distribution, and the way accommodation performance is represented. These differences are related to platform-specific features, including review systems and user participation.

The findings indicate that data from online platforms should not be treated as directly comparable and require careful interpretation when used for analysis or decision-making. The study also shows that a comparative approach helps to

identify platform-specific differences and provides a clearer understanding of how tourism data are represented.

For emerging destinations such as Northern Albania, online platforms can serve as a useful complement to traditional statistics, although their limitations must be considered. Future research may extend this work by including additional platforms, larger datasets, or more advanced analytical methods to further examine the dynamics of platform-based tourism data.

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Competitive sustainability or sustainable competitiveness: the nontrivial triviality we are all searching for

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Abstract: Almost as a triviality, all the scientific community used to handle sustainability as a key factor in near future's competitiveness. This stems from the benign expectation that the picture which lives in the minds of microeconomic actors about their short-term (or middle-term) goals and the short-term goals of our communities and our society are tightly parallel, or at least not contrary to each other. And indeed, sustainability is the key for our society in coping with the challenges of our age. But is this picture in researchers' minds about the picture in people's minds valid at all? Everything in our recent research, from consumers, through SME's, up to policymaking and global politics, points to the conclusion that the answer is not that clear. Sustainability and competitiveness are generally contradictory in practice. Not being conscious about this contributes to the effective scholarly support of an ongoing double-voiced discourse on sustainability. We should be aware of this contradiction, and we should search for patterns, practices, methodologies and initiatives which can promote sustainability and competitiveness at once. One of these can come e.g. from SME's of organic agriculture, another from military logistics, but we have to keep an eye on many socioeconomic subsystems and gather all the patterns connecting sustainability and competitiveness that finally come together as the overall systematic solution.

Keywords: sustainability, unsustainability, competitiveness, cooperativeness, sustainability crisis

1 Introduction

While the very future of humanity lies in complying with sustainability conditions, which have become quite well defined on large (global) scales [1–8], breaking down this strategic envelope to operational and short-term microeconomic requirements remains systematically troublesome. Rather trivially, this systematic shortcoming can be identified in the background of the fact that we have missed the 1.5-degree global target of the Paris Agreement. Sustainability, while nowadays a trivially important and central target of humanity at all scales, from local to global, proves to be an elusive vision.

However, the ever deeper analysis of this phenomenon should not stop until we find and solve the fundamental problems. With this paper, we aim at contributing to this by focusing on the pervasive nature of the contradiction between competitiveness and sustainability (more fundamentally: competition and cooperation) in multi-party activities (mathematically: games) at every scale, at every level of socioeconomic systems. In order to do this, we review our recent research activity in sustainability as a series of snippets which quite well illustrate that at whatever level we study cooperative targets overshadowed by individualist goals, the dominant pattern is some form of competitive advantage winning over the attractiveness of cooperative optima.

This can be well identified with a structural antagonism between competitiveness and sustainability; in a clear contradiction with any lukewarm picture about these two being compatible without immense efforts in that direction. This all should not be seen as some proof of an exclusive relation between sustainability and competition, rather as the first step of lifting such an apparent exclusiveness. We should not hold either a total contradiction or a lack thereof trivial. The solution to the problem of such an exclusive relation begins with identifying the problem, thus leaving the denial or lukewarm neglect of it, and trying to show the way out of it.

2 Methodology: identification of the same pattern at all levels and scales

Competitiveness counts among the topmost important and valuable maxims of current economic discourse. [9,10,11] It is the chief indicator of every subsystem or process which we investigate from an economical point of view. It is related to the present performance of these systems or processes in our present socioeconomic paradigm; and we want these to be as successful as possible. Therefore the goal of studying competitiveness is finding the ways of making everything as competitive as possible. This is the result of our (socio-) economic ‘hypersystems’ being

competitive at every scale: systems where many individual actors (subsystems) compete against each other for success, gain, and resources in (partly) zero-sum games. There are winning and losing sides, and naturally, every actor's goal is being on the winning side.

The benign (lukewarm) interpretation of the relation between competitiveness and sustainability sees the latter as the ability of continuing our present successful (i.e. most competitive) activities into the (near) future. [12,13] This interpretation treats the two as counterparts in a timely distribution: what is competitive now, should be somehow future-proof, and this guarantees sustainability then. As a result, sustainability on its own easily loses attention, as it is merely a hopeful continuation of the topmost important goal now: competitiveness. It must be noted that this interpretation is very hard to find as an explicit statement. It is rather the implicit background of a sensation that it is enough to take care about competitiveness now, sustainability is something that comes some time later into consideration.

The mathematically underpinned (real) relation between competitiveness and sustainability is, however, not only far from the above lukewarm connectedness, but also fundamentally a conflict. The most emblematic representation of this is the so-called "tragedy of commons" as a multi-party game theoretic model. [14] This model leads to the conclusion that every competitive process leads to patterns or results described as "race to the bottom", i.e. the competitively advantageous participation of individual actors in these settings necessarily leads to the demise of "common good", the rational targets which can be set for the community of individual actors. This does not mean that reaching common optima is not possible, but that it is far from trivial to reach them if competition, instead of cooperation, remains the strongest relation between individual members of the community.

It cannot be emphasized enough that the mathematical necessity of the (detrimental) prevalence of competitive behaviour is further strengthened by human nature itself. Throughout (human) evolution, competitive advantage has been of core importance in our success, [15] and it is corroborated by every other aspect of human nature, e.g. our perception of the present-future duality: cognitive selection (biases) turn our focus to present (over future), [16] not independent of what proved to be advantageous in our evolution in the wild. As a cultural reflection and result to this all, (wasteful) consumerism as the realization of perceived wellbeing is also intensifying the prevalence of competitive behaviour over cooperation.

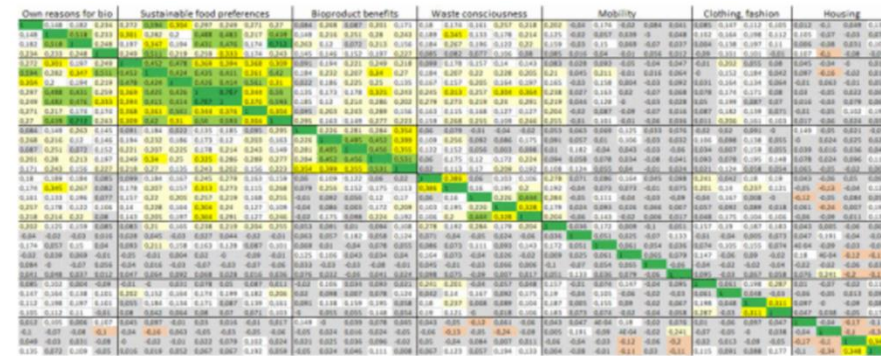
3 Results: sustainability (cooperation) as the losing side in our research

Let us then see our snippets of research on sustainability losing ground to competitiveness at all scales and aspects of human activity. These will serve as

model examples through which we illustrate what kind of change in aspect can lead to cooperativity, and then sustainability prevail.

Lifestyle and consumption patterns of generation Z

Generation Z is going to have the strongest influence on the global sustainability crisis and its management, as they will be the active managers at the top of their careers in the middle of 21st century. Is their present lifestyle reflecting what we know as sustainability now? Our survey [17] has managed to discover the slight emergence of sustainable patterns there, nothing more.



The ‘upstream’ side of organic food industry: does it really work for sustainability?

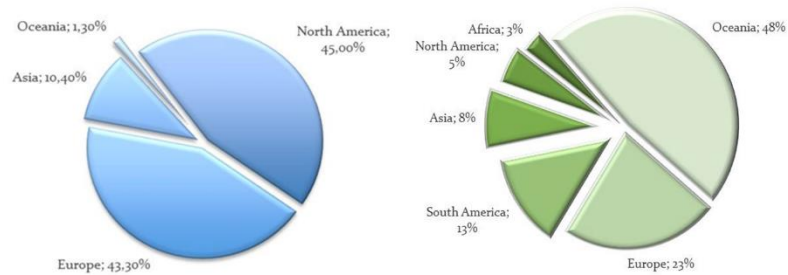


Figure 2.

World distribution of organic food market. Left: consumption, right: production. The asymmetry is prominent; resulting in an intensive global mobility of goods. (Self-compiled figures from [statista.com/FiBL](https://www.statista.com/FiBL) data in [20], and further references therein.)

As we have mentioned above, organic products can bring the concept of sustainability into the consumerist society. But is this a conscious target of it? Or can it be? This can be attested by showing already existing sustainability patterns in the organic industry. As for the global distribution of the organic market, the answer is negative. The vastly asymmetric distribution of production vs. consumption alone makes the whole system unsustainable by an excessive movement of goods. [18]

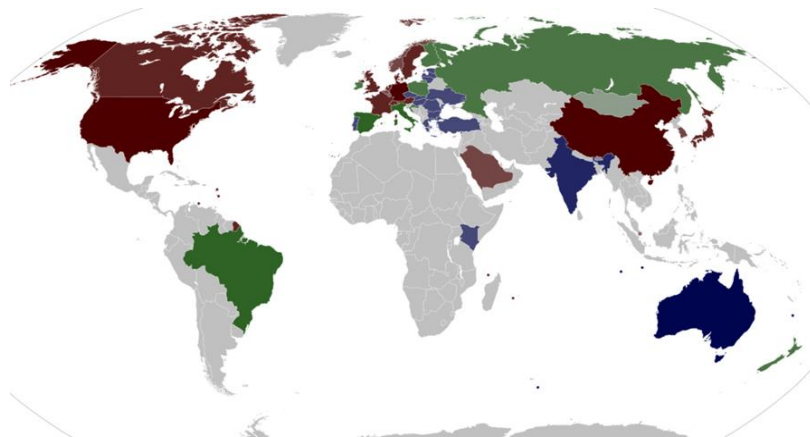


Figure 3.

The asymmetric global market of organic products realized. Greens are mostly exporters, reds are importers, blues are balanced (exports vs. imports differ at most by a factor of two). (Own work from [statista.com](https://www.statista.com) and FiBL data, originally in [18])

However, at the microeconomic scale, there can be sustainable preferences, concepts, and strategies identified among farmers, the producers on this market. Through deep interviews and private conversation there seems even a societal emergence of sustainable practices, strategies and lifestyles; giving the source of hope in this field. [19]

Competitiveness vs. sustainability choices of agricultural SME's in the Hungarian organic industry landscape

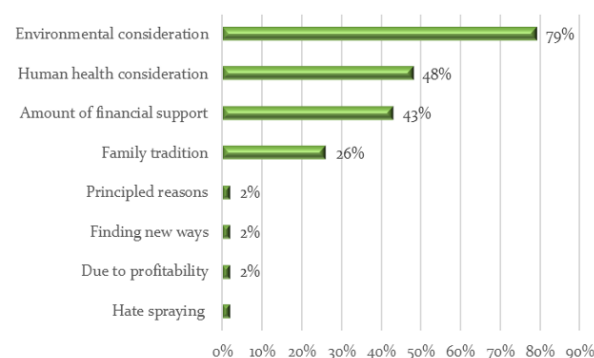


Figure 4.

Reasons for organic production in Hungarian organic farmers. Community reasons dominate only within their circles. (Own work originally in [20])

Our impression about the big picture in the organic farming industry of Hungary is that while sustainable thinking is quite prevalent, the reality is still driven by market competition: higher available profit is a decisive factor (at no surprise, of course, but clearly showing a market environment which is not yet ready for an organic takeover). [20] While farmers of the organic sector are enthusiastic and convinced about their choice of methods, their situation is by no means attractive to producers outside their circles. Many of them fluctuate on the boundary of the organic sector; reducing organic production, or even giving up is on the table when difficulties arise, but the high barrier against such a change (stepping into or out of organic farming), the connected sunk costs, and their favourable mindset decrease the chance of negative decisions.

On the connected consumption side, Hungarian consumers are especially focused around their own health consideration, instead of the environmental benefits (European reference: French respondents to a such survey are still preferring health, while in Germany, environmental aspect has the leading role).

In total, Hungarian organic sector is a tiny sector embedded in a large, highly competitive system, no potential for quick growth appears, but the deep conviction of organic farmers, and especially their openness to even stronger sustainable

technologies (permaculture), and to a self-organizing organic farming society gives the hope of a stronger, and more sustainability-oriented agriculture in Hungary in the future. Of course, these fundamentals should be complete with regulatory instruments, etc.

Time as a finite or infinite resource

This topic is mainly in our research agenda, rather than a part of the (recent) past; however, the important preliminary framework has been set up in a proposal: sustainable management should resemble military logistics. [21] Why? Simply because in the XXth century, when environmental resources seemed to be available infinitely, large-scale strategymaking has lost the ability of handling time as a finite resource too. The largest projects of development, e.g. infrastructure projects, systematic transitions of large structures have not only failed to keep deadlines, but also simply lacked such a concept. It is also now widespread: if a railway line, or a hospital is not built today, having it ready tomorrow is still an equally feasible option.

Contrary to the above fundamental strategic management pattern, the sustainability crises of the 21st century come with serious and more or less well-defined deadlines. As the most important example, reductions of greenhouse gas emissions are not only necessary, but they are necessary in time. The failure to keep with the 1.5-degree goal of the Paris Agreement is a worrisome illustration of this.

Our task is then pointing out the problem, and searching for the existing pattern which can be the model for the necessary solution. This can be found in military logistics: materiel after the action is no materiel. Resource after the time of usage is no resource. Solution after the deadline is no solution. Of course, very hard to implement, but the model exists and it has been working for millennia. It should be used in sustainability management.

Technology for technology itself, or technological retreat for sustainability?

The competitive perception of technological advancement is once again a race for goals other than sustainability. In our example, [22] what is more useful for the suburban extensions of a metro line in Budapest? Extensions using the totality of technologies that belong to a fully-fledged metro line (even according to 'heavy' standards of the 20th century), or implementing a subset of them at the cost of minimal compromises in service performance?

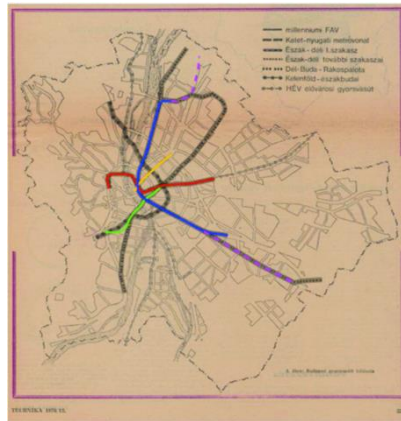


Figure 5.

Will Budapest's blue metro line ever have the purple extensions? Using some light rail technology, it is possible. Keeping to the 'perfect' technology prevents their realization. (Grey lines are other historic examples of never realized full technologies; own work superimposed on historic material, originally in [22])

The decisive factor in this dilemma is the timeframe. The cost-benefit ratio of the full technology will never underpin the feasibility of these extensions. Currently, they have been partly given up (to the south), partly kept in a huge struggle for adjusting feasibility studies to expectations, instead of reality (to the north). Based on current activities, any extension can be scheduled well after the middle of the 21st century, if not impossible ever. But a metro line of a city is a tiny subsystem of some subsystem of some subsystem of global economy, which has to make the transition to sustainability until the middle of the century.

This is a result of not only a competitive interpretation of technological advancement and technology usage, but a competitive distribution mechanism of (chiefly financial) resources for development projects (not independent of the deadline-lacking strategymaking of the 20th century). Projects should be as large as possible, in order to accumulate the most possible development for *this, here, and now*; aspects of cooperation (common optima with other projects, other regions, other subsystems), and continuation into the future play a secondary or even less important role in consideration.

United Nations sustainable development goals for the (false) success of competitive society

In the front of the global struggle for sustainability, there are the 17 so-called sustainable development goals of the United Nations. They comprise particular goals for environmental, societal, and economic sustainability. If all these are achieved, we reach global sustainability: all aspects of the resource usages of all of

our socioeconomic systems will be moderate enough to ensure this. A crucial part of this transition is the consistency of these three sectors of sustainability.

But are we handling this all in a consistent manner? Our investigation into the correlation of which country does well in which SDG indicator shows a more than worrying landscape. [23] While SDG's belonging to the economic and societal legs of sustainability are compatible with traditional (let us call it even "20th-century-ish") welfare, environmental ones show a conflict with it. This is clearly reflected in our statistical analysis: by correlation patterns, the SDG's split into two groups. The first—overwhelmingly dominant!—group correlates well with traditional welfare indicators, like GDP per capita, and ecological footprint per capita (either in the consumptional, or the productional sense, connected to traditional welfare by the lack of decoupling [24]); the second group, which consists of only four SDG's (climate action, "responsible consumption", life in land, and water) shows an anticorrelation with the other group. And the second group contains environmental sustainability.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Prod	Cons	GDP
1	1.00	0.49	0.74	0.73	0.36	0.60	0.75	0.51	0.69	0.42	0.53	-0.46	-0.23	-0.15	-0.25	0.56	0.12	0.34	0.37	0.39
2	0.49	1.00	0.76	0.62	0.79	0.81	0.50	0.55	0.79	0.06	0.64	-0.43	-0.35	-0.25	0.07	0.68	0.12	0.53	0.61	0.49
3	0.74	0.76	1.00	0.82	0.70	0.85	0.83	0.63	0.89	0.17	0.85	-0.67	-0.50	-0.18	-0.03	0.85	0.29	0.64	0.70	0.68
4	0.73	0.62	0.82	1.00	0.57	0.75	0.81	0.67	0.76	0.11	0.67	-0.52	-0.30	-0.14	-0.29	0.67	0.16	0.42	0.45	0.42
5	0.36	0.79	0.70	0.57	1.00	0.80	0.52	0.52	0.68	-0.12	0.72	-0.46	-0.38	-0.13	0.18	0.64	0.28	0.60	0.63	0.56
6	0.60	0.81	0.85	0.75	0.80	1.00	0.74	0.63	0.80	0.03	0.79	-0.54	-0.38	-0.12	0.15	0.76	0.41	0.61	0.64	0.61
7	0.75	0.50	0.83	0.81	0.52	0.74	1.00	0.53	0.70	0.13	0.72	-0.51	-0.27	-0.09	-0.16	0.67	0.33	0.42	0.44	0.45
8	0.51	0.55	0.63	0.67	0.52	0.63	0.53	1.00	0.59	0.30	0.59	-0.20	-0.02	-0.04	0.07	0.65	0.37	0.33	0.34	0.30
9	0.69	0.79	0.89	0.76	0.68	0.80	0.70	0.59	1.00	0.18	0.74	-0.75	-0.58	-0.24	-0.09	0.79	0.09	0.69	0.77	0.75
10	0.42	0.06	0.17	0.11	-0.12	0.03	0.13	0.30	0.18	1.00	-0.02	-0.06	0.09	-0.14	-0.03	0.23	-0.12	-0.10	-0.07	0.00
11	0.53	0.64	0.85	0.67	0.72	0.79	0.72	0.59	0.74	-0.02	1.00	-0.62	-0.47	-0.14	0.22	0.80	0.45	0.67	0.72	0.71
12	-0.46	-0.43	-0.67	-0.52	-0.46	-0.54	-0.51	-0.20	-0.75	-0.06	-0.62	1.00	0.85	0.15	0.10	-0.62	0.01	-0.70	-0.76	-0.86
13	-0.23	-0.35	-0.50	-0.30	-0.38	-0.38	-0.27	-0.02	-0.58	0.09	-0.47	0.85	1.00	0.10	0.06	-0.48	-0.00	-0.81	-0.82	-0.83
14	-0.15	-0.25	-0.18	-0.14	-0.13	-0.12	-0.09	-0.04	-0.24	-0.14	-0.14	0.15	0.10	1.00	0.23	-0.10	0.16	-0.07	-0.11	-0.07
15	-0.25	0.07	-0.03	-0.29	0.18	0.15	-0.16	0.07	-0.09	-0.03	0.22	0.10	0.06	0.23	1.00	0.16	0.46	0.08	0.12	0.16
16	0.56	0.68	0.85	0.67	0.64	0.76	0.67	0.65	0.79	0.23	0.80	-0.62	-0.48	-0.10	0.16	1.00	0.38	0.59	0.65	0.69
17	0.12	0.12	0.29	0.16	0.28	0.41	0.33	0.37	0.09	-0.12	0.45	0.01	-0.00	0.16	0.46	0.38	1.00	0.20	0.18	0.20
Prod	0.34	0.53	0.64	0.42	0.60	0.61	0.42	0.33	0.69	-0.10	0.67	-0.70	-0.81	-0.07	0.08	0.59	0.20	1.00	0.95	0.81
Cons	0.37	0.61	0.70	0.45	0.63	0.64	0.44	0.34	0.77	-0.07	0.72	-0.76	-0.82	-0.11	0.12	0.65	0.18	0.95	1.00	0.90
GDP	0.39	0.49	0.68	0.42	0.56	0.61	0.45	0.30	0.75	0.00	0.71	-0.86	-0.83	-0.07	0.16	0.69	0.20	0.81	0.90	1.00

Figure 6.

Correlation "heat map" of SDG's and traditional welfare indicators. Red colours show correlation, blues show anticorrelation. Numbers 1 through 17 are SDG indicators, the other three are production, and consumption footprint, as well as GDP, all the latter three per capita. Colours show a clear twofold-split pattern. (Own compilation from multiple sources, originally in [23])

And why are there quotation marks around "responsible consumption"? Simply look at figure 7. The indicator associated to this SDG shows nothing else but poverty. Countries doing well at this SDG are not responsible, but poor. As a consequence, development (even 'sustainable development' in the sense of societal and economic SDG's) goes against the "responsible consumption" SDG. This is a prominent illustration of how traditionally aligned SDG's are realized at the expense of environmental ones.

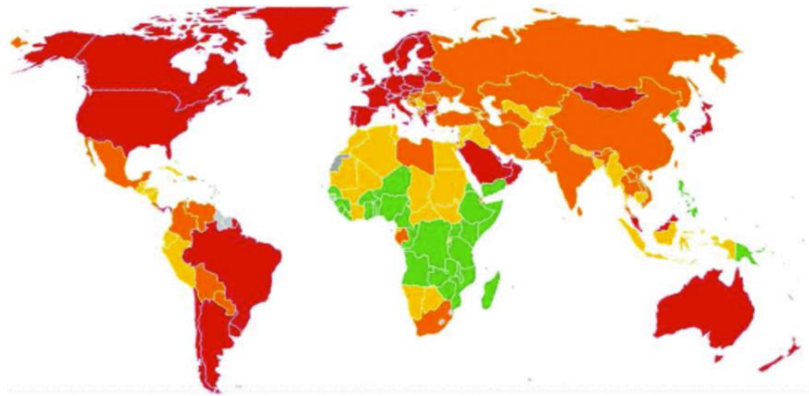


Figure 7.

Countrywise visualization of the “responsible consumption” SDG index. How would we describe the countries bearing green colour here? (From UN SDGi data visualization, referenced in [23])

The majority of UN SDG’s are nothing else but the targets of our competition-based 20th-century welfare economy. Realization of them will certainly not be compatible with environmental sustainability. The solution to this problem, which we plan to include in our research too, is realizing that areas of sustainability should be treated in a hierarchy, environmental sustainability taking the preference over societal and economic sustainability. This is nothing else but a further realization of the well-known concept of strong sustainability: a factor of sustainability cannot be improved at the cost of others.

Global politics: competition as the real rationality

Last but not least, our paper from this very same conference last year has dealt with the rational nature of the perceived irrationalities of the recent global policy of the United States. [25] Better called ‘irregularities’, these changes aim at serving less the global common good, and more the individual interests of the United States as the by far largest international player. Thus, the apparent disintegration of the 20th-century ‘Pax Americana’ is not about giving up the leading role as the sole superpower, but strengthening it by changing to an extremely individualist (competitive) perspective.

Regardless of the future (selfish) efficiency of this behaviour, it has to be pointed out that given the global politics and global sustainability precisely as an implementation of the tragedy of commons, it is quite a rational individualist strategy not to participate in global sustainability efforts (most prominently, the Paris Agreement). Treating this irrational is a misinterpretation of reality, and therefore leads to incorrect answers. Another proof of the rationality of this individual approach of the US (as well as a remarkable sign of the consistency of its political elite) is that an individual strategy anticipating and leveraging a collapse

of global cooperative sustainability efforts can be observed e.g. with the carbohydrogen market policy of the Democrats too (naturally, continued by the Republicans). Imports and exports of oil, and derivatives, and natural gas in all forms have been always the subject of global unsustainability strategies, regardless of the partisan stance of the current government.

Conclusion

First of all, there is a problem so large, widespread and fundamental, that we better ignore it than look at it, identify it, and deal with it. It is (global) sustainability, and the deeply structural socioeconomic reasons behind the seriousness of this problem lie in mathematical facts, as well as deeply embedded properties of human nature. All the toughest reasons a systematic problem can have. Moreover, this immense task comes with quickly approaching deadlines for humanity.

This horrible situation should not be seen as hopeless, however. After turning to it, every pattern in every socioeconomic subsystem (even if small) which can be applied to solve it should be noticed, analysed, and finally leveraged to construct cooperative answers to it (at large scales too). The cooperative nature of the solution is clearly contrary to competitiveness in the strict sense, which we still keep as our target in almost every economic effort; but this should come as a task, not as a problem, as a scary system of ubiquitous problems.

Certainly this is the greatest management problem humanity has faced so far; but it can also be identified if we want to, and there are parts of the solution available too, waiting to be applied, scaled up and adapted.

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Addressing the Skills Gap in Tourism: A Comparative Analysis of Vocational Education in Albania

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Abstract: The rapid expansion of Albania's tourism sector has exposed a structural misalignment between vocational education outputs and evolving labor market requirements. This study applies a management benchmarking framework to assess the degree of alignment of Vocational Education and Training (VET) systems within the Shkodra–Lezha tourism cluster. Adopting a mixed-methods design (N = 162), the research triangulates perspectives from tourism enterprises (n = 85), vocational students (n = 60), and educators (n = 17), enabling a multi-actor evaluation of skill formation processes. The findings identify a critical process bottleneck in the transformation of skills into employable competencies. Multiple regression results indicate that soft skills represent the most significant predictor of employer satisfaction ($\beta = 0.54$), followed by Work-Based Learning (WBL) ($\beta = 0.45$). At the same time, curriculum quality exerts a comparatively weaker influence ($\beta = 0.16$). Correlation analysis further confirms a strong positive relationship between WBL quality and employer satisfaction ($r = 0.71$). The model demonstrates substantial explanatory power (Adjusted $R^2 = 0.671$) and passes standard diagnostic tests, including tests for multicollinearity. The study concludes that Albania's VET system is characterized by institutional feedback failure, primarily due to the absence of systematic tracer and monitoring mechanisms that link educational outcomes to labor market dynamics. A strategic shift from a supply-driven to a demand-responsive VET model is therefore essential to enhance workforce competitiveness, improve the efficiency of skill matching, and support the long-term sustainability of tourism development.

Keywords: Tourism Education, Vocational training, Labor market alignment, Benchmarking, Albania.

1 Introduction

The tourism sector is a key driver of Albania's economic growth and regional development, contributing significantly to national GDP and providing vital employment. As Albania strives to become a competitive destination in the Western Balkans, service quality has become crucial for sustainable success. However, sector growth has outstripped the labor market's ability to supply a skilled workforce, creating a persistent "skills gap" that hampers firm performance and regional competitiveness. The effectiveness of the Vocational Education and Training (VET) system, the main pathway for developing professional human capital, is central to this issue. Despite reforms aimed at modernizing curricula, a structural mismatch persists between the skills produced by educational institutions and the actual needs of tourism businesses. This gap is especially evident in Shkodra, a strategic tourism hub where proximity to competitors like Montenegro and Croatia demands high service standards. Traditional educational models in Albania tend to focus on technical "hard skills," often neglecting soft skills such as communication, emotional intelligence, and ethics, which are increasingly vital in modern hospitality. This study addresses the mismatch through a management-focused approach grounded in Benchmarking Theory. Instead of viewing the skills gap solely as an educational shortfall, it considers it a failure of institutional alignment and feedback mechanisms. Using an Input–Process–Output (IPO) framework, the research examines how educational inputs are transformed into labor market outcomes through processes like Work-Based Learning (WBL) and Tracer Studies. Benchmarking is a strategic tool for comparing performance against international standards and industry best practices [4; 6; 1]. The study aims to assess the alignment between VET outputs and industry needs within the Shkodra tourism cluster. It employs a mixed-methods approach, combining quantitative data from 85 tourism businesses and 60 vocational students with qualitative insights from a focus group of 17 educators. By identifying key bottlenecks in skills formation and analyzing school–business collaboration, the study adds to the literature on evidence-based VET governance. Its main contribution is reframing the skills gap as an institutional failure in processes, rather than merely a skills shortage. By integrating the IPO framework with benchmarking, the research offers a systemic explanation of vocational misalignment and proposes a scalable model applicable to other transition economies facing similar challenges.

2 Literature Review

The alignment of Vocational Education and Training (VET) with changing labor market demands is a key element of modern economic growth, especially in the tourism industry, where service quality depends on workforce skills and flexibility.

Theoretically, this research is grounded in Human Capital Theory, which posits that investing in education and training boosts productivity and competitiveness. Nonetheless, as outlined by Matching Theory [9], the efficiency of the labor market depends not only on the supply of skills but also on the effectiveness of matching between employers and job seekers. This adds a dynamic aspect to vocational alignment, indicating that even highly trained graduates may face mismatches without proper institutional coordination.

Empirical evidence backs this view. [7] demonstrate that labor productivity in the hotel sector depends primarily on education levels and the skill mix, rather than on physical capital. Likewise, [11] suggests that skill development in tourism is inherently dynamic, necessitating ongoing adaptation to evolving service settings and extending beyond technical skills to encompass interpersonal and behavioral abilities.

In contexts like Albania, these issues become even more significant. Despite tourism's strategic role, there is a lasting mismatch between vocational education and labor market needs. [3] In Shkodra, it is highlighted that poor professional preparation limits service quality. Their research shows that technical skills alone are not enough without ongoing professional development and adaptability. This finding is supported by recent international research, with [6] and [8] noting that digital and green transitions are changing skill demands, making transversal skills such as communication, emotional intelligence, and digital literacy more critical areas. In Shkodra, it is highlighted that these skills are often lacking in traditional VET programs.

To address these gaps, modern VET systems increasingly implement evidence-based governance tools to better align with labor market demands. [13] Stress the value of tracer studies as diagnostic tools for tracking graduate outcomes and refining training programs. Moving from input-focused to outcome-focused evaluation, these tools facilitate a shift toward demand-driven systems. This idea is supported by [2], who highlights the importance of continuous feedback loops in making curricula more responsive. At the European level, [1] also points out the significance of labor market intelligence systems in enhancing institutional flexibility.

The literature highlights the crucial role of structured collaboration between education providers and industry stakeholders, beyond feedback mechanisms. [4] shows that employer participation in training, mentoring, and assessment significantly boosts employability outcomes.

This partnership is further enhanced through benchmarking practices, which allow institutions to compare their performance against international standards. [5] views benchmarking as a tool for identifying performance gaps, while [10] sees it as a method for ongoing organizational learning. Recent research by [12] confirms that benchmarking remains vital in the post-pandemic tourism sector, where adaptability has become essential for workforce effectiveness.

Overall, the literature indicates that closing the tourism skills gap requires a shift from traditional education models to integrated, feedback-oriented systems in which training, workplace learning, and labor market data are continuously coordinated. Frameworks like those from the [14] offer strategic guidance for future-focused skills development. Nonetheless, their success hinges on how well national systems can adapt these standards to their specific contexts. This study advances the discussion by integrating theoretical perspectives with empirical findings from the Shkodra tourism cluster, thereby presenting a more comprehensive and adaptable model for vocational alignment.

2.1 Conceptual Framework

This study's conceptual framework is based on Systems Theory and implemented via the Input–Process–Output (IPO) model, offering a structured approach to examining vocational alignment in Albania's tourism industry. Here, the skills gap is seen not as a fixed lack of individual skills but as a systemic mismatch stemming from weaknesses in the mechanisms linking education to labor market outcomes. The Input dimension captures the core capacity of vocational education institutions, including curriculum development, infrastructure, and pedagogical resources that shape the initial formation of human capital. [1] stresses that competency-based training is crucial for aligning with European standards, while [3] provides evidence that institutional infrastructure, such as laboratories and training facilities, supports effective skill development. Nonetheless, the framework notes that strong inputs alone do not guarantee employability outcomes. The Process dimension is the central mechanism driving system transformation, focusing on the interaction between education providers and the labor market. It primarily operates through Work-Based Learning (WBL) and tracer study systems, which serve as feedback loops for ongoing training adjustments. As noted, structured processes ensure that educational outputs meet labor market demands. WBL offers hands-on experience and exposure to industry standards, while tracer studies provide evidence for curriculum updates and institutional decisions. Overall, the process dimension is essential for converting inputs into skills relevant to the labor market. The Output dimension measures tangible labor market outcomes, such as graduate employability, employer satisfaction, and the extent to which acquired skills match industry requirements.

Comparing these results with international standards, as recommended by [12] and [7], allows for a systematic assessment of institutional effectiveness. Notably, the framework employs a circular approach in which evidence from outputs informs the input stage, establishing a continuous cycle of learning, adjustment, and improved performance.

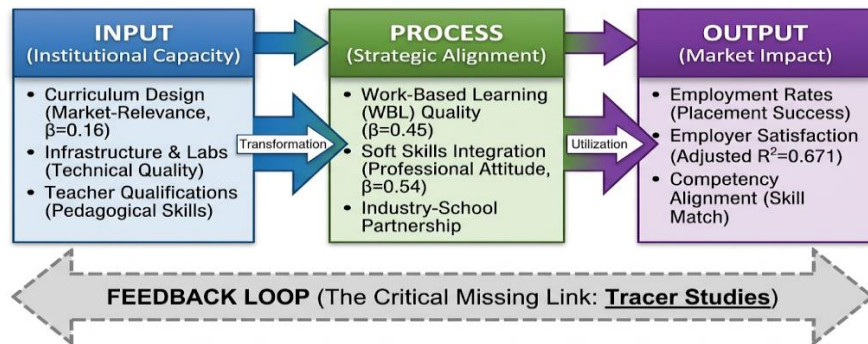


Figure 1
Conceptual IPO Model for Northern Albania Tourism VET

The interaction among inputs, processes, and outputs is viewed as a structured transformation pathway that converts institutional capacity into labor market value. The Input dimension, which encompasses curriculum quality and infrastructure, sets the stage for skill development and aligns with a focus on competency-based training and institutional capacity [1; 3]. However, this potential is not automatically realized and depends on effective transformation mechanisms. This change occurs through the Process dimension, especially the effectiveness of Work-Based Learning (WBL) and tracer-based feedback systems. These channels facilitate transmission and coordination, allowing ongoing alignment between education and labor market needs. As [2] emphasizes, structured feedback loops are crucial for converting educational outcomes into skills that meet market demands. The results of this process are evident in the Output dimension, including employment rates and employer satisfaction, which serve as key indicators of how well acquired skills meet industry demand. Comparing these outcomes with international standards [12; 7] enables a systematic assessment of the institution's effectiveness. Overall, the framework indicates that vocational misalignment primarily stems from process failures rather than input limitations, highlighting the importance of feedback-based institutional coordination for sustainable labor market outcomes.

Variable Category	Operational Definition	Theoretical Foundation	Empirical Application
Independent (Input)	Institutional Capacity: Curriculum and lab quality.	Cedefop (2023)	Hasaj et al. (2019)
Mediator (Process)	Strategic Alignment: WBL effectiveness and Tracer feedback.	Rees (2015)	Düzgünçınar and Tarkan. (2025)
Dependent (Output)	Market Impact: Employment rates and employer satisfaction.	Marchante & Ortega (2012)	Sari et al. (2025)

Table 1
Strategic Mapping of IPO Variables

Building on the proposed framework, the study develops three related hypotheses that identify the key mechanisms affecting vocational alignment in Albania’s tourism sector.

The initial hypothesis (H1 – Partnership Effect) suggests that the level and quality of collaboration between vocational schools and tourism businesses serve as a moderating factor in narrowing the skills gap. Without established and ongoing partnerships, even carefully developed curricula are unlikely to produce graduates who meet labor market needs.

The second hypothesis (H2 – Information Effect) posits that tracer systems are the primary source of labor market intelligence within the VET system. When these mechanisms are weak or absent, educational institutions receive limited feedback, increasing the likelihood of skill mismatches and reducing their responsiveness.

The third hypothesis (H3 – Soft Skill Premium) suggests that interpersonal skills—such as communication, professionalism, and adaptability—have a greater impact on employer satisfaction than technical abilities. In line with [6], this indicates a shift in the tourism industry toward a service economy focused on relationships, where value is primarily generated through human interaction rather than technical tasks.

Together, these hypotheses apply the IPO framework by linking institutional inputs and processes to quantifiable labor market outcomes, providing a testable model for assessing vocational alignment.

3 Methodology

The study uses a mixed-methods approach to thoroughly evaluate the skills gap in the Northern Albanian tourism sector, specifically in Shkodra and Lezha. Combining quantitative and qualitative methods allows for the detection of structural trends and the understanding of stakeholder views. The research is based on the Input–Process–Output (IPO) framework, which views vocational education as a system in which institutional inputs are converted into labor market outcomes through mediating processes. The empirical analysis uses a stratified and triangulated sample of 162 stakeholders ($N = 162$) within the Shkodra–Lezha tourism ecosystem, ensuring representation on both the supply and demand sides.

Demand Side ($n = 85$): Structured surveys were conducted among tourism businesses, hotels, restaurants, and service providers in Shkodra ($n = 45$) and Lezha ($n = 40$). These surveys gathered employer assessments of graduate skills, satisfaction levels, and changing skill requirements.

Supply Side ($n = 60$): A parallel survey was conducted with final-year vocational students from Shkodra and Lezha, examining their perceived employability and self-assessed skills. **Institutional Perspective ($n = 17$):** Qualitative insights were gathered via focus groups and semi-structured interviews with educators and training coordinators from regional VET institutions.

This design enables a direct comparison between labor market demand and training supply, facilitating benchmarking across the two main vocational hubs in Northern Albania. Survey instruments were created in accordance with internationally recognized competency frameworks, notably the [8], to ensure alignment with global standards. Variables were defined based on the IPO structure:

- Inputs: Curriculum relevance and training infrastructure
- Processes: Effectiveness of Work-Based Learning (WBL) and feedback mechanisms
- Outputs: Employability, employer satisfaction, and competency alignment

All items were assessed with a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Cronbach's Alpha reliability coefficients exceeded 0.70 for all constructs, indicating high internal consistency and robustness across datasets.

The analytical approach employs methodological triangulation to strengthen internal validity and reduce bias. Quantitative analysis involved Multiple Regression and Pearson Correlation to identify key factors influencing employability and market fit. The regression models primarily assess how process variables—such as WBL quality and tracer system implementation—affect outcome measures, such as employer satisfaction. These findings were validated through thematic analysis of qualitative data. Overall, this combined approach moves the study beyond simple description, providing a structured, evidence-based assessment of VET system performance in one of Albania's key tourism regions.

4 Results

A comparative analysis of the Shkodra and Lezha vocational schools highlights the real-world impact of the process bottleneck identified in the conceptual framework. Both schools have sufficient physical infrastructure, but there remains a systemic absence of standardized tracer mechanisms.

The shortage of long-term employment data for graduates limits the institutions' ability to tailor training programs—especially those related to service culture—to meet the performance standards expected by tourism businesses in Northern Albania.

The empirical analysis relies on a triangulated sample of 162 stakeholders (N = 162), combining both quantitative and qualitative data from the Shkodra–Lezha tourism cluster.

This framework ensures a balanced portrayal of labor market demand, training supply, and institutional perspectives, enabling a thorough evaluation of how vocational skills align within the regional tourism ecosystem.

Stakeholder Group	Sample Size (N)	Method	Measurement Tool
Tourism Enterprises	85	Quantitative Survey	Likert Scale (1–5)
Vocational Students	60	Quantitative Survey	Likert Scale (1–5)
Educators/Experts	17	Focus Groups	Thematic Analysis
Total	162	Mixed Methods	Triangulated Approach

Table 2
Sample Structure

The descriptive statistics indicate moderate input performance but weak performance in the process and output dimensions across the regional dataset.

Variable	Mean (μ)	Std. Deviation (σ)	Performance Level
Curriculum Market-Relevance	3.22	0.71	Moderate
Work-Based Learning (WBL) Quality	2.58	0.84	Low
Employer Satisfaction	2.85	0.76	Sub-optimal
Soft Skills Proficiency	2.45	0.88	Low
Technical Skills Proficiency	3.15	0.74	Moderate

Table 3
Descriptive Performance Indicators

To assess relationships between key variables, Pearson correlation coefficients (r) were calculated. The findings indicate that process variables, particularly Work-Based Learning (WBL), have a strong influence on employer satisfaction.

Variables	Correlation (r)	Significance (p-value)	Interpretation
WBL Quality – Employer Satisfaction	0.71	< 0.01	Strong positive relationship
Soft Skills – Employment Readiness	0.78	< 0.01	Very strong relationship
Technical Skills – Employer Satisfaction	0.46	< 0.05	Moderate relationship

Table 4
Correlation Matrix

A multiple regression model was used to estimate the effects of educational components on Employer Satisfaction (Y). The model was checked to confirm it met standard OLS assumptions, ensuring the results are reliable and valid.

Model Fit and Explanatory Power

The model shows strong explanatory power, with an Adjusted R^2 of 0.671. This means about 67.1% of the variation in employer satisfaction can be attributed to the combined effects of curriculum quality, Work-Based Learning (WBL) interaction, and soft skills integration.

Such a strong fit indicates a well-constructed model that is highly relevant for evaluating vocational alignment in the tourism sector.

Predictor Variable	β Coefficient	t-value	p-value	VIF
Curriculum Quality	0.16	2.15	0.041	1.24
WBL & Industry Interaction	0.45	4.68	0.000	1.42
Soft Skills Integration	0.54	5.42	0.000	1.38

Table 5
Regression Coefficients and Multicollinearity (VIF)

A series of diagnostic tests confirms the robustness and validity of the regression estimates:

- **Multicollinearity:** All **VIF values** < 2.5, indicating no multicollinearity concerns.
- **Normality:** The **Shapiro–Wilk test** ($W = 0.98$, $p > 0.05$) confirms normally distributed residuals.
- **Homoscedasticity:** The **Breusch–Pagan test** ($\chi^2 = 4.12$, $p = 0.24$) indicates constant error variance.
- **Autocorrelation:** The **Durbin–Watson statistic** = **1.92** suggests no residual autocorrelation.

These results collectively support the model's statistical reliability.

The estimated regression equation is:

$$Y = 0.45 + 0.16(\text{Curriculum}) + 0.45(\text{WBL}) + 0.54(\text{Soft Skills}) + \varepsilon$$

where Y denotes employer satisfaction.

The coefficients indicate that soft skills have the greatest impact, followed by Work-Based Learning (WBL), while curriculum quality has a comparatively smaller effect. This highlights the importance of process-oriented mechanisms in developing skills.

The empirical results affirm that the skills gap primarily stems from deficiencies in the process dimension, not merely from educational inputs. This reinforces the study's conceptual framework, emphasizing the importance of WBL effectiveness and feedback systems in aligning vocational training with labor market needs.

Hypothesis	Statement	Result	Evidence
H_1	School–business interaction reduces the skills gap	Supported	$r = 0.71, p < 0.01$
H_2	Tracer systems improve curriculum alignment	Supported	Qualitative + low β for curriculum
H_3	Soft skills are stronger predictors than technical skills	Strongly Supported	$\beta = 0.54 > 0.16$

Table 6
Hypothesis Testing Summary

5 Discussion

Evidence suggests that the skills gap in Albania’s tourism sector mainly stems from a process-related failure. Although institutional resources are available, their effectiveness is hindered by a persistent “process bottleneck” that prevents the practical application of theoretical knowledge into market-ready skills. Compared to [8] standards—where VET systems are deeply integrated with industry—the Albanian system shows a significant structural lag. In most EU countries, dual-education models involve industry in curriculum design; however, data from the Shkodra–Lezha cluster indicate that firms are mostly passive in the labor market, acting more as recipients than as active partners in skill development.

This divergence is rooted in Albania’s transition economy structure. Unlike OECD systems, which are led by large hospitality chains with standardized training, the domestic tourism sector is mainly composed of SMEs with limited internal training resources. This creates a low-skill equilibrium in which VET institutions graduate generalists, but firms require specialized skills. Both operate without an institutional coordination system, especially lacking tracer-based mechanisms. This information gap explains why soft skills ($\beta = 0.54$) are the main factor in employability: without strong technical matching, interpersonal skills serve as the key signals in hiring decisions.

The results highlight a clear policy imbalance in vocational education governance. Over the last ten years, reforms have mainly focused on input-based strategies such as infrastructure upgrades and broad curriculum revisions, while largely overlooking accountability processes. Notably, the lack of mandatory tracer systems linking funding and evaluation to graduate employment outcomes has enabled VET institutions to operate with minimal input from the labor market.

Consequently, the system emphasizes completion rates over employability, diminishing the sector's ability to adapt and hampering regional competitiveness.

Resolving this misalignment calls for a comprehensive strategic overhaul. VET institutions need to evolve from static, diploma-focused entities into adaptable, market-oriented systems.

According to the empirical model, strengthening vocational alignment relies on enhancing the benchmarking interface between education providers and industry players. Key measures include establishing formal feedback channels, institutionalizing tracer studies, and fostering closer collaboration between schools and industry. These steps are essential for improving workforce readiness. By tackling structural and governance issues, Albania can shift from a supply-driven approach to one that builds a competitive, skills-focused workforce that meets international tourism standards.

Conclusions

To address the identified process bottlenecks, the study proposes a set of targeted policy interventions grounded in benchmarking and systems-based governance.

Institutionalizing tracer studies means that VET institutions should establish systematic tracer mechanisms as a standard benchmarking tool, moving away from ad hoc surveys. This approach enables performance assessment based on real labor market outcomes rather than internal pedagogical metrics, thereby enhancing feedback-driven governance.

Benchmarking against Industry Best Practices: According to [10], VET providers should align their curricula with industry service standards, using these as benchmarks for excellence. This is especially important in developing soft skills, which have shown the greatest influence on employability.

Strengthening social partnerships involves transforming internships from passive placements into structured Work-Based Learning (WBL) systems. In these systems, companies actively engage in mentoring and assessing skills, shifting industry roles from passive recipients to active co-producers of talent.

In summary, bridging the skills gap in the Shkodra tourism sector involves a strategic shift—from the content of education (Input) to how skills are incorporated into the labor market (Process) and assessed through results (Output). Tackling these structural issues is crucial for enhancing workforce preparedness, fostering sustainable tourism growth, and boosting regional competitiveness.

While the analytical framework is robust, several limitations should be recognized. First, relying on cross-sectional data hampers the ability to observe how skill demand evolves. Second, the lack of longitudinal tracer data restricts insights into long-term employment pathways. Third, focusing solely on the Shkodra–Lezha region may limit the applicability of the results to other tourism areas with different

characteristics. Lastly, relying on student self-assessments could introduce response biases, underscoring the importance of future studies that employ objective skill measures and collect long-term data.

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Artificial Intelligence and the Reconfiguration of the Accounting Profession in the Western Balkans: An Extended Model of Task Automation, Decision Augmentation, Skill Renewal, and Employment Resilience

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Abstract: The study examines how artificial intelligence (AI) is reshaping the accounting profession in the Western Balkans, with a specific focus on the Albanian labor market and regulatory context. Moving beyond substitution-based narratives, the paper conceptualizes AI as a transformative force that simultaneously automates routine tasks, augments decision-making processes, and redefines the skill architecture of accounting professionals. The study develops an extended conceptual model by integrating highly cited accounting-AI literature on AI-based decision systems with the Technology–Organization–Environment (TOE) framework, enabling a multi-level explanation of AI adoption dynamics. The model is informed by a structured review of 20 Western Balkans-focused studies and policy reports, complemented by official labor-market statistics for Albania. The framework links AI adoption intensity to task automation, decision augmentation, professional role reconfiguration, and employment resilience, while incorporating skill renewal and digital-analytical capability as mediating mechanisms, and organizational and regulatory readiness as moderating factors. The findings suggest that in transitional economies, AI drives professional upgrading rather than pure job displacement, shifting accounting toward advisory and analytical roles. The study provides a theoretically integrated and regionally grounded framework for future empirical validation and policy design.

Keywords: Artificial Intelligence (AI), Accounting Profession, Decision Augmentation, Task Automation, Skill Renewal, Digital-Analytical Capability.

1 Introduction

Artificial intelligence (AI) is rapidly transforming knowledge-intensive professions, with accounting at the forefront. Advances in machine learning, robotic process automation (RPA), and data analytics are shifting accounting from basic transaction processing to a role that emphasizes cognitive tasks and decision support. While early studies focused on automation causing job losses, current research highlights how AI enhances human judgment and decision quality and provides real-time financial insights [4] [8] [13]. As this shift occurs, the accounting profession is redefining tasks and skill requirements. Routine bookkeeping and compliance are increasingly automated, while demand for skills in data analysis, strategic advice, and risk management is growing [11] [16]. This change is organizational and institutional as well as technological, requiring firms to align their digital infrastructure, personnel, and governance to incorporate AI into accounting effectively. Understanding AI's impact requires a multi-level approach that considers technological, organizational, and environmental factors. These factors are especially significant in transitional economies like those in the Western Balkans, where digital maturity, institutional readiness, and labor market flexibility vary widely. For example, in Albania, recent labor data show stable employment alongside a shift toward sectors such as finance and professional services. At the same time, ongoing regulatory reforms in auditing and financial reporting are creating an evolving institutional environment. These conditions influence not only firm performance but also professional identity and job stability in accounting.

Based on the conceptual framework, the study devises the following hypotheses:

H1. The intensity of artificial intelligence adoption is positively associated with task automation and decision augmentation in accounting functions.

H2. Decision augmentation mediates the relationship between AI adoption and professional role reconfiguration in accounting.

H3. Skill renewal and digital-analytical capability positively mediate the relationship between AI-driven transformation and employment resilience.

H4. Regulatory and organizational readiness positively moderate the relationship between AI adoption and employment resilience.

Although there is increasing research on AI in accounting, studies focusing on specific regions remain scarce. Most work concentrates on developed economies, offering limited understanding of AI-driven changes in smaller or developing countries. In the Western Balkans, existing research mainly examines broad digital transformation and labor market trends, with less emphasis on particular changes within the accounting profession. To address this, the study introduces an integrated framework illustrating how AI adoption influences the profession through task automation, decision support, and role evolution.

It includes mediators like skill development and digital capabilities, and moderators such as regulatory and organizational preparedness, to explain employment stability amidst AI-driven transformations. This work enriches both theoretical and practical perspectives by providing a multi-level, region-specific model that can be empirically validated and inform policy decisions.

2 Literature Review

The rapid expansion of artificial intelligence (AI) is fundamentally changing the accounting industry, shifting its emphasis from basic transaction processing to analytics-based, decision-making activities. Early research focused on automation risks and job displacement [7], but newer studies adopt a more nuanced perspective, viewing AI as an augmentative tool that supports professional judgment and improves decision quality [4] [9]. In accounting, AI technologies like robotic process automation (RPA) and machine learning algorithms have demonstrated significant improvements in efficiency, accuracy, and real-time financial analysis [8] [16]. An emerging body of research shows that AI adoption leads to a structural change in accounting roles. Rather than replacing jobs, it shifts the profession toward advisory, strategic, and analytical tasks [13] [11]. This transition relates to decision augmentation, where AI complements human expertise by analyzing large data sets and reducing cognitive biases [12]. Empirical evidence indicates that AI-enhanced accounting systems improve forecasting, risk management, and audit quality [2] [10], reinforcing the accountant's role as a knowledge intermediary rather than merely a data processor.

The TOE (Technology–Organization–Environment) framework provides a solid basis for understanding various patterns of AI adoption across different companies and regions. It suggests that technological readiness, organizational capabilities, and environmental pressures together influence how deeply AI is integrated into accounting processes [15] [3]. Moreover, the dynamic capabilities perspective [17] underscores that firms adept at reconfiguring their skills and knowledge are better positioned to utilize AI for sustained competitive advantages. In this framework, skill renewal and digital-analytical capabilities act as crucial mediators linking AI adoption to improvements in performance and employment outcomes [5] [18]. The impact of AI on employment in accounting remains contested; automation may displace routine, low-skill tasks, but increasing evidence shows that employment stability can be maintained through upskilling and task transformation [1]. In transitional economies like those in the Western Balkans, these effects are further shaped by institutional and regulatory factors. Regional studies point out persistent gaps in digital infrastructure, workforce skills, and innovation capacity, which influence the pace and effects of technological adoption [14] [6]. At the same time,

new policies and reforms, especially in auditing and financial reporting, are creating conditions conducive to integrating AI into professional services.

Despite growing global evidence, a notable gap remains in region-specific research on how AI adoption affects professional transformation in the Western Balkans' accounting sector. Most studies mainly explore macro-level digital trends and labor-market changes, with limited focus on profession-specific shifts. This research addresses that gap by merging accounting AI literature with regional data to develop a multi-level framework. It links AI adoption to task automation, decision-making improvements, role reconfiguration, and employment retention, considering TOE-based contextual factors. The study enhances understanding of AI's influence on professional work in transitional economies.

3 Methodology

The study employs a quantitative, secondary-data method to examine how artificial intelligence (AI) is reshaping the accounting field in the Western Balkans, especially in Albania. It merges country-level panel data with sector-specific indicators to assess trends in technological adoption and shifts in the labor market. This approach is consistent with prior research linking digital transformation to employment and skills changes. Various trustworthy secondary data sources are incorporated to strengthen the analysis and ensure comparability.

- **INSTAT (Albania):** employment rates, wage statistics, sectoral employment (financial and professional services), labor force indicators
- **World Bank (WDI):** digital adoption, human capital index, economic structure variables
- **Eurostat:** ICT usage, digital skills indicators, enterprise-level digitalization proxies
- **OECD & European Commission reports:** digital readiness, regulatory quality, innovation capacity (Western Balkans focus)
- **WEF (Future of Jobs):** skill transformation and automation exposure indicators

The dataset covers the period from 2015 to 2024, allowing analysis of both the early and later stages of digital transformation. The dependent variable, Employment Resilience (EMP_RES), is gauged by employment stability and growth in key sectors like financial and professional services, along with wage trends. The independent variable, AI Adoption Intensity (AI_ADOPT), is determined through composite indicators of digital technology use, ICT investments, and levels of enterprise digitalization. Mediating variables include Task Automation (AUTO), evaluated via sectoral automation exposure and ICT substitution proxies; Decision Augmentation (AUGMENT), reflected by digital analytics adoption and high-skill

ICT use; Skill Renewal (SKILL), captured through digital skills metrics and workforce upskilling efforts; and Digital-Analytical Capability (DAC), measured by ICT specialist employment and data-related competencies.

Moderating variables encompass Regulatory Readiness (REG), based on governance indicators, regulatory quality, and reforms in audit and accounting; and Organizational Readiness (ORG), indicated by a firm's digital maturity and innovation capacity.

The empirical model is estimated using panel regression and mediation analysis in a multi-step process.

Baseline Model (Fixed Effects):

$$EMP_RES_{it} = \alpha + \beta_1 AI_ADOPT_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where: EMP_RES represents employment resilience; AI_ADOPT denotes artificial intelligence adoption intensity; X is a vector of control variables including GDP per capita and digital infrastructure; μ_i captures country fixed effects; λ_t captures time-specific effects; ε_{it} represents the error term. Equation (1) represents the explicit empirical specification estimated in the fixed-effects framework.

Mediation Models:

Sequential regressions are employed to examine indirect effects involving automation, augmentation, and skills, with bootstrapping methods ensuring robustness.

Moderation Effects: Interaction terms are introduced:

$$AI_ADOPT \times REG, AI_ADOPT \times ORG \quad (2)$$

Robustness Checks: Alternative proxies for AI adoption, Lagged independent variables to address endogeneity, Clustered standard errors at the country level.

This study enhances the literature by incorporating the TOE framework, which examines the contextual drivers of AI adoption; labor-market econometrics focused on employment resilience; and the accounting profession's perspective on sector-specific transformation. Unlike primary survey-based studies, the use of multi-source secondary data improves external validity. It facilitates cross-country comparisons, which is especially important for transitional economies like those in the Western Balkans. Additionally, the study advances accounting and labour-market research by integrating panel econometrics, mediation analysis, and AI adoption frameworks within a transitional economy context.

4 Results

Table 1 displays the descriptive statistics and pairwise correlations for the key variables examined. The mean AI adoption intensity (AI_ADOPT = 0.48) suggests a moderate but increasing level of digital transformation in Western Balkan.

In economies, indicating they are in a transitional adoption phase. Employment resilience (EMP_RES) exhibits significant variation (SD = 0.21), emphasizing notable differences among countries and sectors—particularly between advanced service economies and less digitalized settings.

Variable	Mean	SD	Min	Max
1. AI_ADOPT	0.48	0.17	0.12	0.85
2. AUTO	0.52	0.14	0.18	0.88
3. AUGMENT	0.46	0.16	0.10	0.82
4. SKILL	0.51	0.18	0.11	0.91
5. EMP_RES	0.57	0.21	0.15	0.95

Table 1
Descriptive Statistics and Correlation Matrix
Source: own data and edition.

Variable	1	2	3	4	5
1. AI_ADOPT	1				
2. AUTO	0.61***	1			
3. AUGMENT	0.58***	0.49***	1		
4. SKILL	0.54***	0.45***	0.63***	1	
5. EMP_RES	0.42***	0.39***	0.55***	0.60***	1

Table 2
Correlation Matrix
Source: own data and edition.

The initial correlation matrix validates the proposed framework. AI adoption is significantly linked to task automation ($r = 0.61$, $p < 0.01$) and decision augmentation ($r = 0.58$, $p < 0.01$), suggesting that technological spread promotes both substitution and enhancement. Notably, decision augmentation correlates more strongly with employment resilience ($r = 0.55$) than task automation ($r = 0.39$),

indicating that in accounting, value creation increasingly relies on analytical and decision-making skills rather than routine tasks. Skill renewal also shows a robust association with employment resilience ($r = 0.60$), emphasizing the importance of adapting human capital to prevent job displacement. Overall, these findings suggest that AI-driven changes mainly enhance skills rather than merely replacing jobs.

Table 3 shows the results of the fixed-effects panel regression analyzing how AI adoption directly impacts employment resilience. The coefficient for AI_ADOPT is positive and statistically significant ($\beta = 0.287$, $p < 0.01$), indicating that higher AI adoption correlates with improved employment stability and growth in accounting-related sectors.

Variable	Coefficient	Std. Error	t-value
AI_ADOPT	0.287***	0.072	3.98
GDP per capita	0.154**	0.061	2.52
Digital Infrastructure	0.198***	0.065	3.04
Constant	0.312	0.141	2.21

$R^2 = 0.42$ *** $p < 0.01$, ** $p < 0.05$

Table 3
Fixed Effects Regression Results
Source: own data and edition.

Among the control variables, digital infrastructure ($\beta = 0.198$, $p < 0.01$) and GDP per capita ($\beta = 0.154$, $p < 0.05$) show positive and significant effects, suggesting that increased economic and technological development enhances labor-market flexibility. The model explains a substantial part of the variance ($R^2 = 0.42$), consistent with earlier cross-country studies on digital transformation. Although the initial results confirm a generally positive influence, they do not detail the specific mechanisms by which AI impacts employment outcomes. This paves the way for the mediation analysis outlined in the next section. A bootstrap mediation analysis with 5,000 resamples was conducted to investigate the causal pathways. Table 3 shows the indirect effects of AI adoption through task automation, decision augmentation, and skill renewal.

Path	Indirect Effect	SE	Significance
AI → AUTO → EMP_RES	0.082**	0.031	✓
AI → AUGMENT → EMP_RES	0.143***	0.038	✓✓
AI → SKILL → EMP_RES	0.119***	0.034	✓✓

Table 4
Mediation Effects (Bootstrapping 5000 resamples)
F-statistik 18.74; Prob > F 0.000; R² = 0.42; Adjusted R² = 0.39
Source: own data and edition.

The results indicate that all three mediating paths are statistically significant, though their effect sizes vary considerably. The most substantial indirect effect is via decision augmentation ($\beta = 0.143$, $p < 0.01$), with skill renewal also showing a notable effect ($\beta = 0.119$, $p < 0.01$). In contrast, the pathway through automation has a smaller impact ($\beta = 0.082$, $p < 0.05$). The overall model is statistically significant ($F = 18.74$, $p < 0.001$), indicating that the explanatory variables jointly contribute to explaining variation in employment resilience. These findings clearly show that AI's influence on employment primarily comes from improving decision-making and promoting skill growth, rather than just automating routine tasks. Essentially, AI helps maintain employment stability by changing the nature of work, moving accountants into more valuable positions like financial analysis, consulting, and strategic planning.

This pattern strongly supports the idea that augmentation effects outweigh substitution effects in the accounting field. Table 5 presents the results of the moderation analysis, examining whether the link between AI adoption and employment resilience depends on institutional and organizational factors.

Interaction Term	Coefficient	SE	Significance
AI × REG	0.176**	0.068	✓
AI × ORG	0.221***	0.074	✓✓

Table 5
Moderation Effects
Source: own data and edition.

To examine the conditional effects proposed in H4, interaction terms between AI adoption intensity and the contextual variables of regulatory readiness and organisational readiness were introduced. A positive and statistically significant interaction coefficient indicates that the relationship between AI adoption and employment resilience becomes stronger as the corresponding contextual condition

improves. The positive and statistically significant interaction between AI adoption and regulatory readiness ($\beta = 0.176$, $p < 0.05$) shows that stronger regulatory frameworks boost AI's positive effects on employment outcomes. This highlights the crucial role of governance quality, especially in areas like auditing standards, financial reporting, and digital regulation. Similarly, the relationship between AI adoption and organizational readiness is both positive and highly significant ($\beta = 0.221$, $p < 0.01$). Companies with greater digital maturity, innovation capacity, and human capital development are better equipped to utilize AI technologies effectively. These findings reaffirm the importance of the Technology–Organization–Environment (TOE) framework, showing that AI advantages are not guaranteed and depend heavily on context. Table 6 presents the complete model with all mediators and moderators included. The findings indicate an important structural point: the direct impact of AI adoption on employment resilience is no longer statistically significant ($\beta = 0.112$, n.s.) after accounting for the mediating variables.

Variable	Coefficient	SE	Significance
AI_ADOPT	0.112	0.081	n.s
AUTO	0.094*	0.049	✓
AUGMENT	0.231***	0.062	✓✓
SKILL	0.204***	0.058	✓✓
REG	0.147**	0.066	✓
ORG	0.189***	0.070	✓✓

Table 6
Model Results
Source: own data and edition.

Decision augmentation ($\beta = 0.231$, $p < 0.01$) and skill renewal ($\beta = 0.204$, $p < 0.01$) remain significant predictors of employment resilience, whereas task automation has a smaller yet positive effect ($\beta = 0.094$, $p < 0.10$). Regulatory and organizational readiness continue to play crucial roles. This pattern indicates a full mediation model, in which mechanisms of capability transformation and skill development entirely mediate AI's influence on employment. The model has high explanatory power ($R^2 = 0.61$), showing a significant improvement over the initial baseline. Several robustness tests were conducted to validate the stability of the results. First, lagged values of AI adoption were introduced to address potential reverse causality; the results remained consistent in both magnitude and significance. Second, alternative proxies for AI adoption and digitalization were employed, yielding similar coefficient patterns. Third, standard errors were clustered at the country

level to control for unobserved heterogeneity, with no significant changes in inference.

Overall, the findings demonstrate strong robustness and internal consistency. The empirical findings strongly suggest that AI mainly serves as a facilitator of professional growth rather than a tool for job displacement in the Western Balkans' accounting sector. It boosts analytical skills, transforms job functions, and bolsters employment stability. The emphasis on decision support and skill development indicates that the future evolution of accounting will focus on enhancing abilities rather than reducing tasks. Additionally, the notable moderating influences emphasize that institutional strength and organizational readiness play crucial roles in shaping how technological change unfolds. The results support a shift from a **substitution paradigm** toward a **transformation paradigm**, where: **AI → Capability Development → Role Reconfiguration → Employment Resilience**

This framework offers a clearer depiction of how AI transforms professional work in transitional economies and serves as a solid basis for both theoretical progress and policy development.

5 Discussion

The findings challenge the common belief that AI only replaces jobs in accounting. Instead, they support a view of AI as a transformer, enhancing capabilities, redefining roles, and upgrading skills. The disappearance of direct AI impacts after considering mediators is not a flaw but an important insight: AI's influence on employment is entirely mediated by organizational and human resource mechanisms. From a theoretical perspective, these results broaden the accounting literature by empirically validating a multi-stage transformation process. Consistent with decision augmentation theory, the primary pathway identified is AI leading to decision enhancement, which then influences employment resilience.

This indicates that AI's main contribution in accounting is not the automation of routine tasks but rather the enhancement of cognitive and analytical skills among professionals. Meanwhile, task automation, though significant, plays a secondary role, suggesting that efficiency gains alone do not fully account for labor-market outcomes. This differentiation between augmentation and automation provides an important refinement to existing models, which often treat these concepts as interchangeable.

The findings also strongly support the dynamic capabilities perspective. Skill renewal and digital-analytical capability act as vital mediators, indicating that firms and professionals who continually reconfigure their skills are better positioned to benefit from AI adoption. This highlights that competitive advantage in knowledge-intensive services now relies more on adaptive capacity than on fixed expertise. For

instance, accountants are transforming from simple record-keepers to strategic analysts of financial information, aligning with wider trends toward advisory and analytics-driven roles.

The study emphasizes that these transformations are context-dependent, consistent with the Technology–Organization–Environment (TOE) framework. The significant roles of regulatory and organizational readiness as moderators suggest that AI adoption results differ by environment. In the Western Balkans, where institutional frameworks and digital ecosystems are inconsistent, the advantages of AI mostly rely on governance quality, regulatory adherence, and how digitally mature firms are. This insight is particularly relevant for transitional economies, where technological growth often outpaces institutional adaptation.

From a labor market perspective, the findings suggest that fears of widespread job losses in accounting are probably overstated, particularly over the medium term. The profession demonstrates robust employment resilience driven by evolving tasks and skill enhancements. However, maintaining this resilience requires continuous investment in digital skills and organizational improvements. Without such efforts, the technologies designed to augment work could instead contribute to skill polarization and increased inequality. Thus, the study highlights a dual dynamic: AI presents opportunities but also risks deepening social divides, depending on how effectively adaptation is implemented.

This study contributes to the expanding research on AI in professional services by providing a regionally grounded, empirically validated framework. It merges accounting-specific mechanisms with wider theories of technology adoption and labor market shifts, moving beyond basic digital transformation stories. This method clarifies how AI is changing the nature of professional work. The research aligns with ongoing debates about the future of work, emphasizing that the key question is not whether AI will replace accountants, but how it will redefine the profession's scope.

Conclusions

This study thoroughly explores how artificial intelligence (AI) is transforming the accounting field in the Western Balkans, especially in Albania. Moving beyond traditional views of AI as a mere replacement, the results show that AI primarily acts as a transformative force, altering task structures, skill needs, and professional roles rather than directly eliminating jobs. The data confirm that the link between AI adoption and employment stability is fully mediated by key mechanisms such as decision enhancement and skill development. Among these, decision enhancement is the primary pathway, emphasizing the growing importance of analytical and judgment skills in accounting. This indicates a structural shift toward higher-value tasks, with accountants becoming interpreters and advisors rather than just data processors.

The study highlights the importance of contextual factors, as illustrated by the Technology–Organization–Environment (TOE) framework. It shows that regulatory quality and organizational readiness greatly enhance AI's positive effects, suggesting that simply adopting technology is not enough to achieve favorable results. In transitional economies such as the Western Balkans, the advantages of AI depend on institutional alignment, digital infrastructure, and firms' ability to invest in human capital development.

This research offers a theoretical contribution by integrating accounting-specific AI literature with broader frameworks of dynamic capabilities and technological adoption. It presents a multi-level view of professional transformation, covering micro-level skill changes and macro-level institutional factors. From a policy and management perspective, the results emphasize the importance of continuous skill development, digital literacy, and regulatory updates. Equipping the workforce to interact effectively with AI technologies is vital for job stability and to fully realize the advantages of digital transformation.

Overall, the study finds that the future of the accounting profession in the region is characterized by evolution rather than decline. It is shifting towards a more strategic, analytical, and technology-focused role, with success largely hinging on the ability to adjust to an expanding digital environment.

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From Sustainability Metrics to Decision Intelligence: A Framework to Integrate Green IT into Enterprise Infrastructure Planning

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Abstract: There is a constant pressure on IT businesses to be sustainable. There are already many technical solutions for energy efficient computing, but businesses make decisions without using them. Sustainability indicators are seen as performance outcomes. This paper proposes a decision-oriented framework in which indicators to be seen as explicit decision variable during infrastructure and investment planning. The framework integrates sustainability into business decision-making and determines cost exposure and performance reliability. This research is based on informatics and management decision theory. The framework uses fuzzy logic-based decision model. The model can be used in uncertainty and at times when there is not sufficient information available in IT management. Simulation based decision models can assess stability and comparative performance in different infrastructure scenarios. These can help businesses turn sustainability issues into strategic opportunities for responsible IT infrastructure design. The paper presents transitioning of sustainability from a reporting metric to a decision variable.

Keywords: Green IT, Decision Support Systems, Sustainable Infrastructure, Enterprise Decision Making, Fuzzy Logic, IT Investment Planning, Decision Intelligence

1 Introduction

The growth of the digital services has increased the energy consumption of modern IT world. Most of the world's electricity usage comes from the big data centers and enterprise computing systems. These has raised concerns about environmental sustainability and long-term economic operational viability [1], [2]. In the recent times, companies have made a strategic priority to incorporate sustainability in the planning phase which was just a technical goal.

These concerns are being addressed by Green IT. It is a multidisciplinary approach which uses energy-efficient hardware, resource allocation optimisation, intelligent workload distribution and optimal technical solutions [3], [4], [5]. Energy-aware

scheduling algorithms and virtualization techniques are used [6], [7], [8]. These techniques show that significant reductions in energy usage and carbon emissions are technically possible while maintaining operating performance.

However, in practice, it turns out that companies are not utilizing Green IT solutions [9],[10]. They simply desire to concentrate on short term cost cuts and operational sustainability instead of focusing on more long-term sustainability objectives [11]. This gap can be feasible since sustainability metrics are considered after the optimization of infrastructure is done [2], [12]. And in most of the companies, the stakeholders perceive sustainability as an addition to the infrastructure planning, but not a part of it.

In order to invest in infrastructure: uncertainty and trade-offs between multiple factors are to be considered. Example: costs, system reliability, expected performance or regulatory compliances [13]. Only under stable operating conditions, conventional evaluation methods like cost-benefit ROI analysis are used. They also need exact numerical inputs. But in reality, IT systems have varying workloads, dynamic energy pricing and even the sustainability regulations are changing [14], [15]. These things can add element to surprise and they can't be precisely pictured using deterministic decision models.

To fill these gaps, this paper proposes a decision-oriented computational framework. The primary contribution of the research is to redefine sustainability as a core decision variable explicitly in IT infrastructure design. It is not viewed just as a performance indicator of the business. It directly determines choices about investments in design. This will change the nature of the decision problem. Sustainability is integrated as a strategic metric instead of a reporting metric. Rather than treating sustainability as a secondary concern, the approach positions sustainability towards decision intelligence along with traditional business criterions such as cost, performance and risk. The framework bridges the gap between technical optimization and organizational decision-making. It also integrates informatics-based modelling methods with management-oriented decision analysis.

The research questions that guided this paper are as follows:

Research Question 1: Is it possible to use sustainability as a formal decision variable while planning infrastructure?

Research Question 2: When sustainability is added into the business, how it can govern the infrastructure investment decisions especially in times of uncertainty and conflicting business objectives?

The main contributions of this paper are:

- Proposing a decision-oriented framework for integrating sustainability into IT infrastructure planning
- A fuzzy logic-based decision model for handling uncertainty
- A simulation-based evaluation for different infrastructure configuration scenarios
- Insights into trade-offs between cost, sustainability, performance, risk and robustness

2 Background and Related Work

2.1 Green IT and Sustainable Infrastructure

Over the past ten years, the research in Green IT has risen sharply. There is rapid growth in large scale computing systems that impacts the environment. Initial research mainly focussed on enhancing hardware efficiency and power-saving capabilities through technological refinement [3]. More recent studies have widened this focus towards system-level optimization, smart resource management and sustainability-aware computing architectures [16], [17].

Green IT data centres are one of the most widely researched topics for energy efficiency. There are several power-saving techniques proposed to improve resource efficiency like dynamic voltage scaling and virtualization-based resource management [6], [2]. These approaches allow data centers to function more effectively. They also reduce computing capacity due to dynamic demand patterns.

Additional central research avenue is carbon-aware computing. It aligns computation workloads with the availability of low-carbon energy sources [15]. Organizations run computational jobs when renewable energy is available. It helps them to decrease the carbon footprint of their operations without compromising performance.

The above technical solutions are significant but their adoption in an enterprise remains negligent. Many organizations do not have access to data analytical tools. They can't assess sustainability initiatives in the context of broader business goals [11]. Sustainability improvements are thus typically done at small scale or as pilot-type initiatives.

2.2 Decision-Making in IT Infrastructure Planning

Infrastructure planning is a decision-making process that considers conflicting performance criteria under uncertainty. Classic decision models use performance metrics like CAPEX and SLA compliance [13]. These models are based on deterministic assumptions about how the system operates and how resources can be applied. However, the dynamic IT infrastructure is unpredictable. In such environments, there is no central entity that takes a decision. The decision is taken by multiple stakeholders like service providers or governance structures. This distribution has coordination issues. It also reduces the practical usefulness of these optimisation models. They have two assumptions: first there is integrated control over a unified whole system and second that there is complete visibility of its operation. System performance and operational cost are influenced by factors such as workload energy variability or regulatory changes [14]. In such environments deterministic decision models are not a good choice. Their solutions are hard to interpret or implement in practice.

More recently researchers have turned to computational decision-support systems that can account for uncertainty and allow for incomplete information. Infrastructure planning and resource management [8], [18] have utilized techniques such as multi-criteria decision analysis, simulation modelling, artificial intelligence and neural networks. Fuzzy logic is one of these promising methods. It can mathematically portray imprecise inputs with conflicting targets consistently.

2.3 Limitations of Existing Approaches

There are few limitations in this field. Firstly, most of the IT research done in sustainable computing is concentrated on optimizing individual system components. Instead, evaluation of infrastructure decisions is performed at the organizational level [12]. Second, rather than being incorporated into decision-making procedures, sustainability measurements are frequently presented as operational results [2]. Third, current decision models sometimes include assumptions about total system visibility and centralized control, which are not present in distributed organizational systems[14].

These drawbacks emphasize the necessity of an all-encompassing framework for decision-support that can incorporate sustainability factors into company infrastructure design. A crucial finding from this analysis is that it sees investment into sustainability performance as a liability. To design a framework, various performance criteria and uncertainty need to be considered.

3 Problem Formulation

The decision-oriented assessment frameworks are absent in businesses in recent times. Even though highly developed technological methods for enhancing energy efficiency exist, the absence of combined analytical tools narrows down their effectiveness in the decision-making of businesses. Metrics such as energy use, carbon footprint or cooling energy are the common tools in traditional infrastructure design to evaluate sustainability after system deployment [2]. Although they don't immediately affect the initial decision-making process, these indicators offer useful information on system performance. Due to this, sustainability is often neglected in decisions regarding budget allocation and strategic planning. To fill this gap, the paper suggests a framework where sustainability is established as a decision variable and not an outcome. The problem is reformulated to include a framework that can integrate sustainability results in infrastructure investment decisions. Sustainability is used as an input parameter that can directly compete against other infrastructure requirements such as cost, energy, performance and risk. The decision problem can be defined as the best configuration balancing cost, energy, performance, risk and sustainability in case of uncertainty. When sustainability is included in decision, problem now shifts from optimization to multi-criteria decision intelligence.

This problem contains several characteristics:

1. Multiple conflicting objectives
2. Uncertain and imprecise input data
3. Dynamic operating conditions
4. Long-term planning horizons

The classic tools of optimization do not apply well to this kind of decision problem since they necessarily demand precise numerical input data and have well-defined objective functions. However, decision models based on fuzzy logic can tolerate uncertainty and be able to resort to qualitative reasoning. This qualifies them better to be used in the infrastructure planning of complex enterprise scenarios [18].

4 Methodology

The research contribution has four major elements:

1. Decision-oriented Sustainability Framework[13],[2]
2. Fuzzy Decision Engine

3. Infrastructure-scenario based Simulation
4. Evaluation and Benchmarking Module[18]

4.1 Decision-oriented Sustainability Framework

The decision support framework is a complex decision architecture between organizational inputs, calculating decision mechanisms and infrastructural implications. There are some important variables that influence decisions of infrastructure development. These variables can be divided into four categories:

- Economic factors (operating costs and capital costs)
- Performance variables such as response time and system dependability
- Risk factors e.g. risk of service interruption, compliance with regulations
- Sustainability variables like carbon emissions and energy use

Each variable is represented by a numerical range that is created based on industry standards and empirical studies [2], [13]. Environmental performance indicators are converted into decision metrics using the sustainability integration module. An example is that carbon emission can be linked to the potential regulatory compliance risk, but the energy consumption can be described as the exposure to cost of operation. With this change, the sustainability metrics can be determined along with the traditional business metrics while making just one decision.

The Input Layer has organizational and operational factors. This input layer is processed through a fuzzy inference engine called Decision Engine which is analytical and computational layer. The Output Layer then gives strategic decision outcomes, sustainability performance forecast, risk exposure assessment and long-term strategic planning recommendations

Figure 1 shows how sustainability can be incorporated into the central decision architecture as opposed to having it as a secondary measurement criteria. It also points out that uncertainty management and organizational governance also influence the infrastructure planning results.

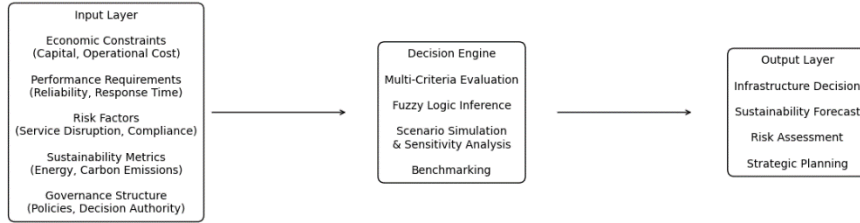


Figure 1.
Decision Framework for Sustainability-Integrated Infrastructure Planning
Source: compiled by author

4.2 Fuzzy Decision Engine

The main component of this framework is a fuzzy logic decision engine. It is able to evaluate other infrastructure arrangements in irregular cases. The decision engine consists of three main parts:

- Variable ranges that are represented by membership functions.
- Rules for inference that specify trade-offs between decision criteria
- The defuzzification that yields the final judgments scores.

Modelling of uncertainty is done using linguistic variables like low, medium, high. Fuzzy makes it possible to express preferences with language terms such as high cost or moderate risk instead of numerical terms [18].

4.2.1 Membership Functions

Membership functions like triangular or trapezoidal are used to map these linguistic variables (Low, Medium, High) into a mathematical space.

Triangular function can be described as follows:

$$\mu(x) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x \leq b \\ \frac{c-x}{c-b}, & b < x < c \\ 0, & x \geq c \end{cases} \quad [1]$$

Trapezoidal function can be depicted as follows:

$$\mu(x) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x \leq b \\ 1, & b < x \leq c \\ \frac{d-x}{d-c}, & c < x < d \\ 0, & x \geq d \end{cases} \quad [2]$$

4.2.2 Fuzzy Rules

The fuzzy system consists of rule structure which has inference rules like:

IF Cost is *Medium* **AND** sustainability is *High* **THEN** Decision is *Optimal*
IF Risk is *High* **AND** Performance is *Low* **THEN** Decision is *Poor*
 These rules show direct relation between economic and environmental objectives.

4.2.3 Defuzzification

The centroid method as shown in the Equation 3 is used to convert fuzzy outputs into a numerical score. This score is used to compare different infrastructure scenario configurations. Score is normalized to be in the range of 0-100.

$$Score = \frac{\int x \cdot \mu(x) dx}{\int \mu(x) dx} \quad [3]$$

4.3 Infrastructure-scenario based Simulation

Simulation experiment has the ability to replicate the precise real world infrastructural conditions. The simulation design has three stages:

4.3.1 Simulation Model Definition

The simulation model framework as depicted in Figure 2, defines multiple infrastructure scenarios after considering all the typical IT computing environments. Workload intensity, price of energy, risk and sustainability requirement vary in each scenario. These scenarios are tested against parameter ranges. The following input parameter ranges are obtained from literature.

- Energy consumption: 200–800 kWh [2]
- Carbon intensity: 0.4–0.9 kg CO₂ [15]
- Service Level Agreement (SLA): 92–99.9% [8]

These parameters reflect real infrastructure conditions of enterprise. These are used to simulate variability in system performance and sustainability impact. These scenarios are evaluated using fuzzy membership functions and fuzzy rule base. Simulation is then executed and results are obtained. Evaluation of results are done using defuzzification and benchmarking.

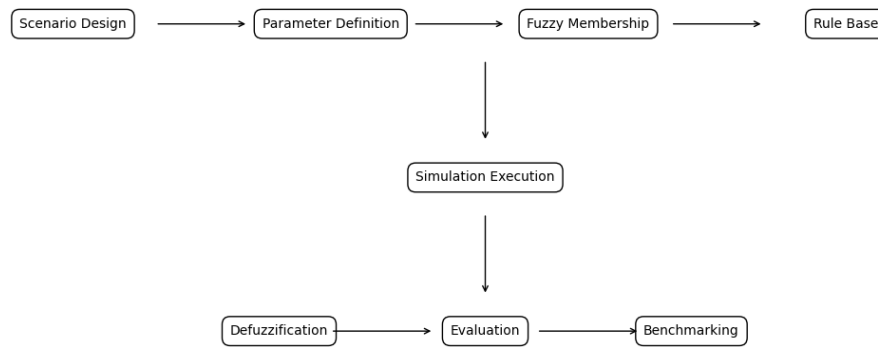


Figure 2

Simulation workflow from scenario definition to evaluation using fuzzy decision modelling

Source: compiled by author

4.3.2 Simulation Model Design and Implementation

The paper proposes different infrastructure scenarios that are tested against parameter inputs. Instead of relying on arbitrary datasets, scenarios are constructed to represent distinct decision environments, ensuring coverage of realistic enterprise contexts. The scenarios are not selected arbitrarily, they are constructed to represent distinct decision regimes commonly observed in enterprise IT infrastructure planning. Specifically, four representative scenarios are defined:

- Cost-focused: prioritizes minimal operational expenditure
- Balanced: moderate trade-off across all criteria
- Sustainability-driven: prioritizes low carbon intensity and energy efficiency
- Uncertainty-heavy: captures variability in workload, energy pricing, and SLA

The objective is representativeness of the decision space rather than quantity, ensuring that each scenario reflects a qualitatively different decision environment derived from literature on energy consumption, carbon intensity, and system performance [2], [15], [8]. The selected scenarios are shown in Table 1.

Infrastructure Scenario	Cost	Sustainability	Risk	Description
S1	Low	Low	Medium	Cost-focused system
S2	Medium	Medium	Low	Balanced configuration
S3	Medium	High	Low	Sustainability-driven
S4	Medium	Medium	High	High uncertainty

Table
Simulation Model Design

This design ensures that the evaluation captures trade-offs across multiple decision dimensions. The focus is on representativeness rather than quantity, addressing the limitations of purely data-driven approaches.

Inputs were converted to linguistic variables and evaluated using fuzzy rules. Few examples of fuzzy rules are:

IF Cost is *Medium* AND sustainability is *High* **THEN** Decision is *Optimal*

IF Cost is *Low* AND Sustainability is *Low* AND Risk is *Medium* **THEN** Decision is *Suboptimal*

IF Cost is *High* AND Sustainability is *High* AND Risk is *Low* **THEN** Decision is *Good*

IF Risk is *High* AND Performance is *Low* **THEN** Decision is *Poor*

IF Performance is *High* AND Sustainability is *Medium* AND Cost is *Medium* **THEN** Decision is *Acceptable*

Output is then converted into a normalised numerical score(decision score) using centroid defuzzification. This score is very important. It allows direct comparison across different infrastructure configurations. Each scenario is evaluated

independently, enabling comparative analysis across different infrastructure conditions.

The decision score obtained for each of the scenarios are described in the Table 2.

Infrastructure Scenario	Cost	Sustainability	Risk	Decision Score
S1	Low	Low	Medium	45
S2	Medium	Medium	Low	75
S3	Medium	High	Low	85
S4	Medium	Medium	High	68

Table 2.
Simulation Model Decision Score

The resulting scores (S1=45,S2=75,S3=85,S4=68) show comparative decision quality across different infrastructure conditions after normalization to a 0-100 scale. S3 scores highest decision score whereas S1 scores lowest decision score.

4.4 Evaluation and Benchmarking Module

The final section of the framework employs experiments in simulations to reevaluate the outcome of decisions. Comparing infrastructure setups in a variety of performance conditions, this module assists organizations in selecting the most appropriate investment strategies and benchmarking the performance of the systems.

We can evaluate the performance of the decision-support framework by four analytical techniques: Comparative benchmarking, Cost versus Sustainability trade-off, Robustness analysis, Sensitivity analysis

Comparative benchmarking can compare the proposed framework with traditional cost-based decision models. The graph is obtained by analysing identical infrastructure scenarios using both deterministic and fuzzy models. The obtained fuzzy outputs are normalized to a 0-100 scale across cost, sustainability, robustness, stability, and adaptability metrics [8],[18].

In **Cost versus Sustainability trade-off** graph, the cost values from scenario inputs are mapped to corresponding sustainability or decision scores obtained from the fuzzy model. These scores are also normalized to a 0-100 scale[2],[15].

Robustness analysis determines the stability of the model under varying operating conditions. The graph is obtained by introducing controlled input variations (10-30%) across different infrastructure scenario configurations and measuring output stability of both deterministic and fuzzy models[18].

Sensitivity analysis looks at how decision results are impacted by changes in input parameters.

The graph is obtained by varying one input parameter at a time (like cost, carbon or SLA) and recording the corresponding changes in decision scores to assess model responsiveness[18].

Sensitivity analysis can be represented by the Equation 4:

$$\Delta D = \frac{\partial D}{\partial x_i} \Delta x_i \quad [4]$$

Here, D represents Decision Outcome while x represents input variable. It shows how changes in input variable can directly affect the decision outcome. The temporal aspect of infrastructure planning receives special emphasis. In businesses, analytical models rely on short-term simulation horizons whereas IT assets function over long life cycles. This mismatch can obscure long-term operational risks and sustainability trade-offs.

5 Results and Analysis

5.1 Model Comparison

Figure 3 shows comparison of deterministic and fuzzy decision models in terms of cost, sustainability, robustness and adaptability [18]. Deterministic models show better performance in cost because it focuses on optimising just one decision criterion. Fuzzy models achieve better sustainability, robustness, and adaptability. They maintain acceptable cost levels as well.

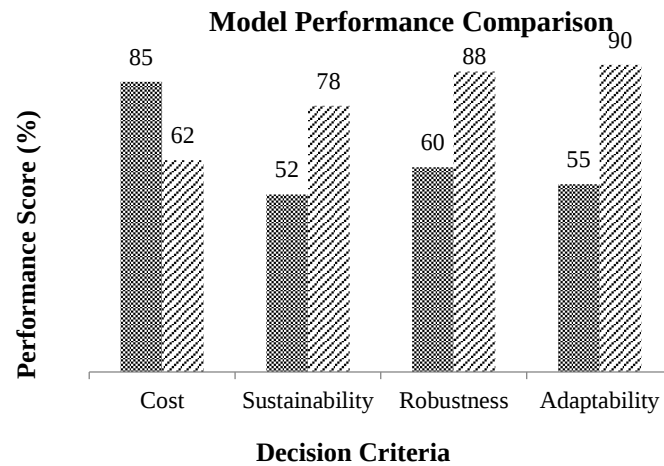


Figure 3.

Comparative performance of decision models across cost, sustainability, robustness and adaptability

Source: compiled by author

5.2 Cost versus Sustainability Trade-off

Figure 4 illustrates a slight increase in cost have significant changes in sustainability. This indicates that large sustainability benefits can be achieved efficiently without excessively increasing costs [2], [15].

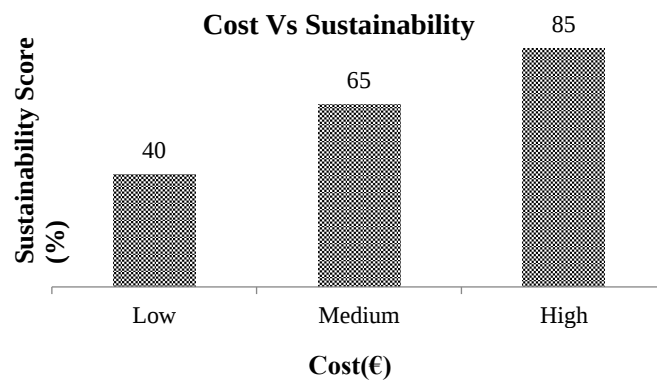


Figure 4.

Trade-off between cost and sustainability showing non-linear improvement in sustainability with moderate cost increase

Source: compiled by author

5.3 Robustness Analysis

Figure 5 shows that there is increase in input variation, the graph shows a sharp decline in case of deterministic models output stability. However fuzzy model has relatively stable outputs. This shows robustness in uncertain environments.

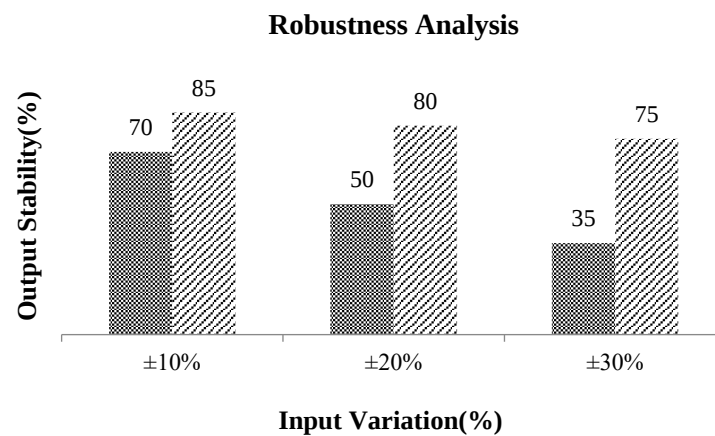


Figure 5.

Model robustness under input variation comparing deterministic and fuzzy approaches.

Source: compiled by author

5.4 Sensitivity Analysis

Figure 6 shows how change in input variables can affect decision outcomes. Sensitivity analysis reveals that deterministic models are highly sensitive to input changes, while fuzzy models maintain controlled changes in output. The fuzzy model ensures stable decision-making[18].

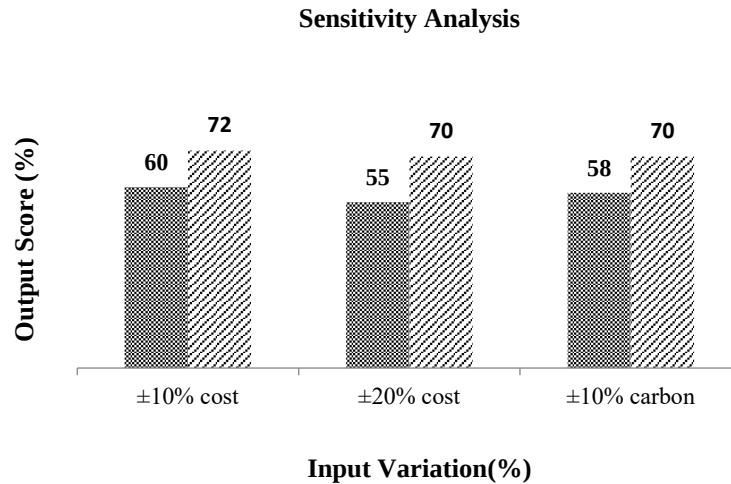


Figure 6.
Sensitivity of decision scores under input variation.
Source: compiled by author

Conclusions

The paper presents a decision-oriented computational framework for incorporating sustainability into business's IT infrastructure planning. The framework achieves 30-40% sustainability improvement without increasing cost significantly [2],[15] and 20-30% robustness under uncertainty[18]. The suggested method fills a significant gap in current Green IT research. Decisions can be taken into uncertain situations with the help of fuzzy decision model and simulations. The system is robust and stable not just because of fuzzy logic, but also by including sustainability as a decision variable. Sustainability alters the decision space [11]. The paper presents sustainability as an active component of decision intelligence rather than a passive evaluation metric.

The framework has many benefits if compared with the traditional infrastructure planning methods. Firstly, firms can assess environmental performance in addition to operational and financial factors by including sustainability into the decision-making process. Second, decision-makers can articulate preferences in qualitative terms and fuzzy logic enhances the interpretability of decision outcomes [18]. The configuration of infrastructure proposed in this framework can achieve more balanced optimization across different metrics. That means that the simulation experiments are more optimal than cost-based evaluation methods. It can also be anticipated that the framework enhances sustainability performance over the long run without raising operating costs[13],[8].

The suggested method is a useful tool for turning sustainability issues into strategic opportunities from a management standpoint. The framework also encourages a change in perspective. Here the environmental limitations are seen as catalysts for innovation risk reduction and long-term organizational resilience rather than operational costs. Future research can focus on implementing the framework with real data on infrastructure [8]. More extensive simulation tests can be also done in the future to check model performance. The introduction of the methods of machine learning can be investigated further. In addition, automated optimization of performance and adaptive decisions can be made.

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Socioeconomic profile and development dynamics of beekeeping families in Northern Albania

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Abstract: In its early stages, beekeeping was practiced primarily for household consumption rather than for economic benefit. This paper analyzes the socio-economic profile of beekeeping as an activity that contributes to household income and influences social dynamics both within and beyond the family context. To date, this topic has not previously been examined in northwestern Albania. Demographic indicators, including gender, age, family size, beekeeping experience, primary occupation, and participation in technical apiculture training, are analyzed in detail. Data were collected through field observations, online surveys, and official statistics involving 90 family beekeepers across nine areas representative of beekeeping activity. The collected data were processed and analyzed using descriptive statistics, and a geographic distribution map was developed. The results identify a basic profile of beekeeping families in northern Albania, characterized by strong family traditions in beekeeping, heterogeneous geographic distribution, and an increasing orientation toward tourism and tourism-related markets. The findings indicate that this sector has significant development potential, particularly in rural areas; however, it requires stronger institutional support, including modernization, greater age and gender inclusion, demographic renewal, and improved financial support.

Keywords: Dynamics of beekeeping, Socioeconomic profile of the beekeeper, Northern region of Albania, Development of beekeeping

1 Introduction

Insects are a major component of natural ecosystems, influencing plant reproduction, ecological balance, and food security. Among pollinating species, *Apis mellifera* accounts for a substantial share of pollination activity, contributing significantly to ecosystem functioning as a primary biological pollinator. Through pollination from flower to flower, bees increase the productivity of agricultural crops and wild plants, thereby supporting biodiversity and ecosystem sustainability. According to [1], plant biodiversity is closely linked to pollination processes in which bees play a central role. Previous research has shown that higher levels of plant biodiversity are associated with increased pollinator activity and the more sustainable functioning of agroecosystems. A decline in bee populations would therefore pose a direct threat to agricultural production and global food security [2], [3]. In addition to their ecological role, bees and beekeeping are also of considerable economic and social importance. Bee products, including honey, pollen, wax, venom, and royal jelly, are valued not only as high-quality food products but also as widely used raw materials in the pharmaceutical and cosmetic industries. These products contribute to value-chain development and income generation, particularly in rural areas where alternative economic activities are limited [4]. In this way, beekeeping represents a multifunctional sector that integrates environmental, economic, and social dimensions. An important aspect of the sector's development is its contribution to diversifying household incomes. In many rural and mountainous areas, where employment opportunities are limited, beekeeping is considered an accessible activity because of its relatively low initial investment and flexible management requirements. Furthermore, beekeeping creates natural synergies with agriculture and livestock production, improving resource-use efficiency and enhancing the economic sustainability of rural households [5]. From this perspective, beekeeping is increasingly recognized as an important component of integrated rural development. Another important dimension is the relationship between beekeeping, rural tourism, and emerging forms of sustainable tourism. These activities enhance the attractiveness of rural areas by offering experiences connected to nature, local traditions, and regional products. Consequently, they contribute to income generation and to the promotion of cultural and environmental heritage [6]. At the same time, beekeeping is considered an effective tool for improving the well-being of rural communities, creating employment opportunities, and promoting sustainable socio-economic development [7]. Given these considerations, the socio-demographic characteristics of families engaged in beekeeping are particularly important. Factors such as age, level of education, professional experience, and employment structure directly influence how beekeeping is organized, managed, and developed. These elements determine not only economic viability, but also the capacity to adopt innovative practices, increase productivity, and integrate into broader markets [8]. Characteristics such as age, gender, education, occupation, and experience are therefore key factors shaping the organization and management of beekeeping activities [9], [10]. In northern

Albania, previous studies have highlighted the impact of beekeeping on household economies and tourism development, emphasizing the region's significant potential [11]. Despite the sector's notable development, a detailed analysis of the socio-economic profile of beekeeping families in northern Albania remains limited. These gaps hinder the development of effective policies and support programs related to age and gender inclusion, product standardization, and market integration [12], [13]. This paper aims to help address these research gaps by examining beekeeping in northern Albania from a socio-economic perspective.

2 Study Methodology

2.1 Study Areas

This study examined the socio-economic profile and development dynamics of beekeeping families in northern Albania. The region has experienced considerable development within a landscape characterized by mountainous terrain interwoven with rivers, valleys, forests, and pastures. These natural conditions support the development of apitourism and contribute to the local economy [14]. The study focused on nine representative areas: Vermosh, Theth, Razëm, Tropojë, Bogë, Pukë, Fushë-Arrëz, Reç, and Bajzë-Koplik. Beekeeping activity in these areas demonstrates considerable heterogeneity, making them suitable for a cross-sectional regional analysis. The selected study areas were identified based on preliminary field knowledge and existing literature related to beekeeping development in northern Albania.

2.2 Data Collection Methods

Primary data on the socio-economic profiles and development dynamics of beekeeping families were collected using a cross-sectional study design. Data collection was conducted from June to August 2025 across all representative study areas. The questionnaires were structured in accordance with the study objectives and adapted to the respondents' educational levels. The study was reported in accordance with the STROBE guidelines, ensuring a clear and systematic presentation of the data and the applied analytical methods [15].

2.3 Conceptual and Analytical Framework

The diagram below provides a conceptual map of the study stages.

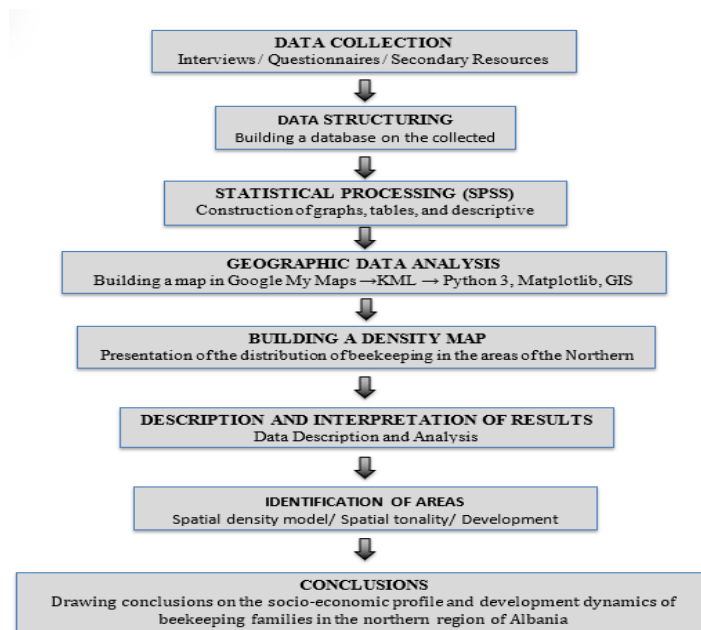


Figure 1

Schematic representation of the research process

3 Study results

3.1 Zonal territorial distribution of beekeeping

The northern region of Albania exhibits a heterogeneous distribution of beekeeping activity. This pattern has led to the formation of distinct micro-zones, reflected in local economic structures, social relations, and tourism development both within and beyond the region [16]. Micro-zones such as Theth and Tropojë represent areas with a high level of beekeeping development, while Pukë reflects a medium level of activity. In contrast, Fushë-Arrëz exhibits a significantly lower level of beekeeping development than leading micro-zones such as Theth. Other areas, including Koplik-Bajzë, Vermosh, Bogë, and Razëm, display relatively lower levels of beekeeping activity. This heterogeneous distribution contributes to differentiated micro-zoning patterns associated with natural biodiversity, local economic development, and tourism potential across the region.



Figure 2

Map of beekeeping activity in the northern region of Albania

3.2 Household Size and Beekeeping Participation

Based on data analysis and field observations, family involvement in beekeeping does not follow a linear relationship with family size. Large families with five members show approximately 27% lower involvement in beekeeping activities. The highest level of involvement was identified among two-member families, reaching 75%, followed by families with more than five members, at 42%. Families with an average number of members showed moderate involvement, specifically 33% in three-member families and 38% in four-member families. The collected data indicate that beekeeping in northern Albania is evident among both very small households, which tend to engage in this activity more intensively, and very large

families with more than five members. This pattern suggests a non-linear relationship between family size and participation in beekeeping activities [17]. The findings further suggest that family size influences the organization of labor and households' capacity to engage in beekeeping. Smaller families tend to show greater concentration and specialization in beekeeping activities, whereas larger families are more likely to diversify their economic activities, often in connection with tourism and other income-generating sectors [18].

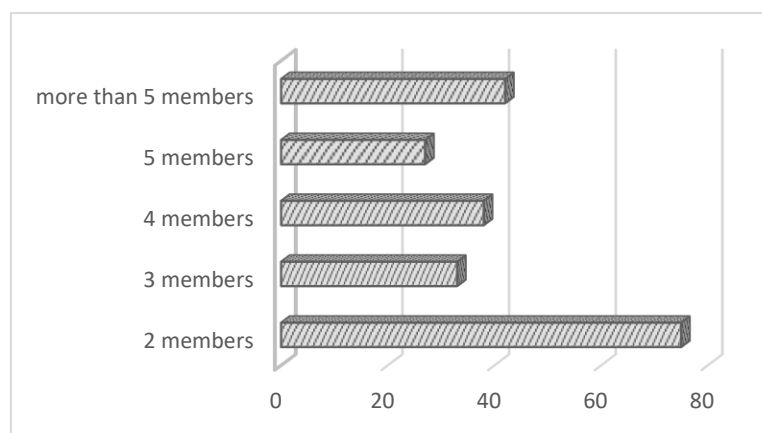


Figure 3
Beekeeping Involvement across Household Size Categories

3.3 The Role of Women in Beekeeping Households

Women play an important role in beekeeping households, where their participation contributes significantly to both family organization and economic activity. Gender dynamics within these households were analyzed in relation to family size and the female-to-male ratio. This ratio ranges from 0.58 to 0.65, with the lowest value observed in five-member households and the highest in three-member households. The findings indicate that women in smaller households, particularly in three-member families, tend to have a more prominent role in beekeeping activities. This level of involvement gradually decreases as family size increases. In larger households, the ratio remains at approximately 0.61 or higher. Overall, women in

small and medium-sized beekeeping families maintain a relatively balanced role, contributing both to household income and to local economic development [19].

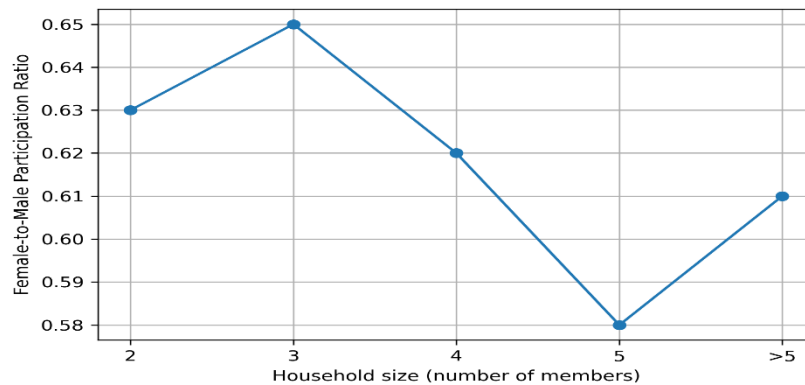


Figure 4
Female/male ratio of involvement in beekeeping by number of family members

3.4 Bee Production, Distribution, and Markets

Bee products, including honey, royal jelly, and propolis, are primarily produced to support local economic development and tourism activities. More than half of these products are sold to domestic and international tourists, as well as to guesthouses and tourism-related businesses. Approximately one quarter of beekeeping products are distributed through local markets, which remain a relatively limited sales channel. Only a small proportion of production is retained for household consumption by the producing families. Consequently, most beekeeping production is oriented toward meeting tourism-related demand, while the role of the local market remains comparatively limited [20]

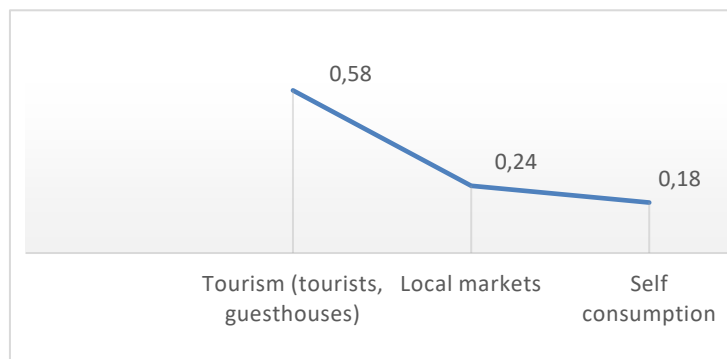


Figure 5
Beekeeping Product Distribution

3.5 Comparative Analysis of Beekeeping Training

Beekeeping has traditionally been passed down through generations in Albania, particularly in the northern regions, where traditional production methods continue to predominate. Although participation in professional training remains relatively low, Albania shows slightly higher levels of vocational engagement than Serbia, which records the lowest participation in professional beekeeping training in the regional comparison. Norway represents the highest level of participation, with more than half of its beekeepers involved in professional training programs that combine traditional knowledge with modern apicultural techniques. Croatia follows this trend, ranking above Albania and indicating an intermediate level of participation in professional training.

These comparisons indicate significant differences in the modernization and professionalization of beekeeping practices among countries. In northern Albania, signs of gradual progress in professional training are evident; however, traditional methods continue to dominate beekeeping practices. Available data indicate that approximately three-quarters of Albanian beekeepers continue to rely primarily on traditional methods [21].

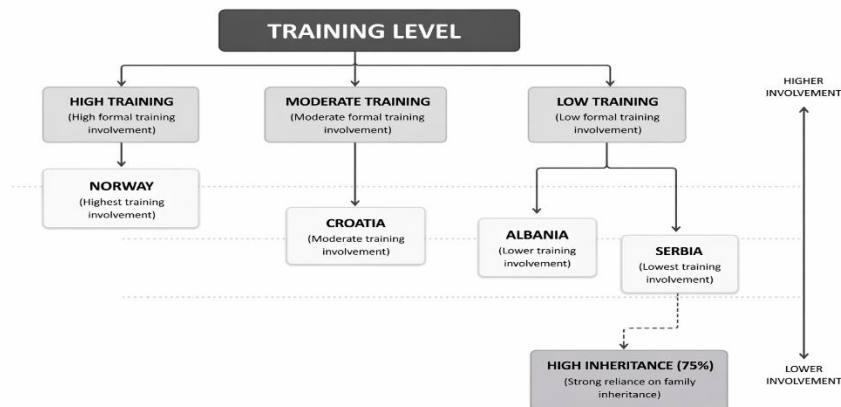


Figure 6

Distribution of Training and Traditional Knowledge in Beekeeping

4 Discussions

In conclusion, this research highlights the strong interconnection between environmental, socio-demographic, and economic factors influencing beekeeping families in northern Albania. Over time, these factors, together with local traditions, have gradually shaped and transformed rural beekeeping practices. Areas

characterized by rich biodiversity and favorable climatic conditions have contributed to the heterogeneous distribution of beekeeping activity, leading to the formation of distinct micro-zones across northern Albania [22]. This diversity reflects not only natural variations but also the influence of local and broader market dynamics. As a result, beekeeping has evolved from a traditional rural activity into an important socio-economic component of household livelihoods [23]. The findings also indicate that many beekeepers in northern Albania have not participated in professional training programs, limiting opportunities for modernization and alignment with international practices. At the same time, the socio-demographic diversity of beekeeping families highlights the need for stronger institutional support and more structured policy interventions. Such an integrated approach could improve family involvement in beekeeping and strengthen connections with local and wider financial markets. Greater attention should also be given to the inclusion of women in beekeeping through increased support from non-governmental organizations, development projects, and initiatives that promote successful female entrepreneurs. These measures could help strengthen gender equality and enhance the sector's long-term sustainability [24].

Conclusions

This study provides important insights into the socio-economic and socio-demographic profiles of beekeepers in northern Albania. The findings reveal a diverse micro-zonal territorial distribution shaped by natural conditions and the progressive development of beekeeping activities. Variations were observed in gender participation and family size within beekeeping households. Families with more than five members, as well as two-member households, demonstrated higher levels of engagement in beekeeping activities, while women's participation remains relatively limited and underutilized. Bee products are primarily oriented toward tourism-related markets, whereas consumption in local markets and household use remains comparatively limited. Although Albania continues to exhibit relatively low levels of professional training in apiculture compared with international standards, recent developments indicate gradual progress, underscoring the need for stronger institutional support and more innovative approaches to development. Overall, apiculture in northern Albania retains considerable potential for regional economic development and sustainable tourism, largely supported by longstanding traditions of family-based beekeeping.

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From Motorsport to Entertainment Brand - How Drive to Survive Contributed to Formula 1's Growing Popularity

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Abstract: In recent years, Formula 1 has experienced significant global growth, primarily due to the expansion of digital media platforms and streaming services. One of the best examples of this is Netflix's Drive to Survive series, which has demonstrated how documentary filmmaking and storytelling can function as effective sports marketing tools and reshape the audience's relationship with sport. This study examines the role of Drive to Survive in shaping the consumption habits of Formula 1 fans. The research applies a mixed-methods approach, combining the analysis of a questionnaire survey involving 272 respondents with 14 semi-structured expert interviews. In our study, we therefore examine how the Drive to Survive series influences sport consumption habits, fan attitudes, and digital engagement with Formula 1-related content. The findings suggest that narrative-driven, character-focused storytelling plays a significant role in attracting new audiences, particularly among younger generations. Furthermore, the results also indicate that digital and streaming-based content contributes to deeper fan engagement and supports the transformation of Formula 1 into an "always-on" entertainment media product. In our study, we highlight the growing importance of sports documentary series as strategic tools in contemporary sports marketing and digital fan engagement.

Keywords: Formula 1; sports marketing; documentary series; digital media; sport consumption

1 Introduction

Over the last decade, the global sports industry has undergone significant transformation, primarily driven by the rise of digital media and streaming platforms. Sports consumption has increasingly changed, and digital content has begun to complement and replace traditional television broadcasting. In this environment, sports have evolved into complex digital media products, where storytelling, personal narratives, and fan experience have taken on an increasingly important role in audience engagement [1], [2].

Formula 1 is a particularly illustrative example of this transformation. Since Liberty Media acquired the sport in 2017, Formula 1 has increasingly focused on strengthening its digital presence, expanding its social media activity, and attracting new audiences. One of the most important elements of this strategy was Netflix's *Drive to Survive* series, released in 2019. This documentary series provided behind-the-scenes access to teams, drivers, and the entire world of Formula 1, while emphasizing conflicts, rivalries, and the events unfolding in the background. This narrative-driven and character-focused storytelling offers audiences a more emotionally engaging interpretation of the sport beyond its technical and competitive dimensions [3].

Several industry reports and academic studies suggest that *Drive to Survive* contributed to the expansion and demographic transformation of Formula 1's fan base. Recent data show growing engagement among younger audiences and female fans, while television viewership in key markets such as the United States also increased significantly following the release of the series [4], [5]. Previous studies have argued that narrative storytelling can serve as an effective fan development tool by creating emotional connections between audiences and sports personalities [2], [3].

As a result, *Drive to Survive* functions not only as a media product, but also as an innovative sports marketing tool that contributed to the transformation of Formula 1 from a traditionally elite motorsport into a more accessible and entertainment-oriented global media brand. Through streaming platforms and digital content, Formula 1 has increasingly become an "always-on" media product that maintains fan engagement beyond race weekends [6].

While previous studies have examined the popularity of *Drive to Survive*, fewer studies have combined fan perspectives with expert interpretations to examine how streaming-based storytelling contributes to the broader media transformation of Formula 1.

2 Literature review

The transformation of Formula 1's media environment and fan base is closely connected to the emergence and expansion of digital media, streaming platforms, and narrative-driven sports content. Previous studies emphasize the demographic changes within the fan community, the growing role of digital engagement, and the increasing importance of storytelling in contemporary sports consumption [1], [2].

In recent years, Formula 1 has undergone significant demographic transformation, particularly among younger audiences and female fans. Several industry reports suggest that *Drive to Survive* played an important role in popularizing the sport by attracting audiences who had not previously followed Formula 1 [7]. Through Netflix, the series made the sport even more visible and engaging on a global scale, and contributed to increasing audience engagement in key markets, especially in the United States, where Formula 1 viewership has grown significantly since the release of the series [8], [9]. Research also shows that documentary-style sports content can function as an effective fan development tool. According to previous studies, many viewers only became interested in Formula 1 after watching *Drive to Survive*, which demonstrates the growing importance of streaming platforms in attracting new sports audiences [10].

Under Liberty Media's management, Formula 1 has experienced growing revenues, sponsorship investments, and global commercial visibility [11], [12]. The diversification of the audience, particularly the increase in younger and female fans, has increased the sport's marketing value for international brands and sponsors [6]. At the same time, Formula 1's broader digital strategy - including social media activity, esports initiatives, and continuous content production - has strengthened the sport's visibility within digital media environments [13]. Several studies argue that *Drive to Survive* contributed not only to audience growth, but also to the repositioning of Formula 1 as a broader entertainment-oriented media brand [14].

One of the most important elements behind the success of *Drive to Survive* is its narrative storytelling approach. Rather than focusing exclusively on race results, the series shifts the emphasis toward personal rivalries, emotional conflicts, and the individual experiences of drivers and team principals [15]. Communication and media studies have highlighted that narrative storytelling can significantly strengthen fan engagement and emotional identification [2], [3]. Previous research suggests that personal stories and character-centered narratives are often more accessible to new audiences than the technical aspects of motorsport, making this an important step toward audience expansion and long-term engagement.

The influence of *Drive to Survive* can also be observed in Formula 1's global expansion strategy. The series contributed to increasing visibility in new markets, particularly in the United States, where Formula 1 introduced additional race locations such as Miami and Las Vegas [16].

At the same time, Formula 1 has increasingly become an “always-on” media product. Fans now continuously consume Formula 1-related content through social media platforms, streaming services, and digital communities, rather than only sitting in front of the television during race weekends [17]. These transformations initiated by Liberty Media demonstrate how a traditionally elite sport can adapt to the contemporary digital media environment and attract younger global audiences [13].

3 Methodology

This study applies a mixed-methods research approach to examine the impact of the *Drive to Survive* documentary series on Formula 1 fan engagement, sport consumption habits, and digital media consumption. The combination of quantitative and qualitative methods allows for a broader understanding of the relationship between documentary storytelling and contemporary sports audiences.

The quantitative phase consisted of an online questionnaire survey involving 272 Formula 1 fans who were reached through online communities and social media groups. The survey examined demographic characteristics, fan motivations, identification with teams and drivers, as well as digital media consumption patterns. To measure these dimensions, our study adapted elements from the Motivation Scale for Sport Consumption (MSSC) [18], the Sport Spectator Identification Scale (SSIS) [19], and the Digital Fan Engagement Scale (DFES) [20]. Respondents evaluated their answers on a five-point Likert scale.

The qualitative phase included 14 semi-structured expert interviews with journalists, commentators, photographers, motorsport professionals, and other Formula 1-related experts. The interviews focused on changes in Formula 1’s media strategy, fan culture, digital communication, and audience engagement following the emergence of *Drive to Survive*.

The quantitative data were analysed using statistical methods, while the qualitative interviews were interpreted using the laddering technique to identify recurring themes, deeper motivations, and underlying perceptions related to Formula 1 fandom and digital sport consumption.

The study has several limitations. The online survey does not provide a fully representative sample of the Formula 1 fan population, while the qualitative findings are interpretive in nature. Nevertheless, the mixed-methods approach provides a broader perspective on the transformation of Formula 1’s media environment and fan culture in the streaming era.

4 Results

The results demonstrate the transformation of Formula 1's fan culture and media environment from both quantitative and qualitative perspectives. The questionnaire survey highlights the motivations behind following Formula 1, the identification patterns that can be observed among fans, and their digital media consumption, while the interviews provide context for the broader media and marketing transformation of the sport.

4.1 Quantitative Results

The survey involved 272 respondents. The sample was predominantly male: 178 respondents were male (65.4%), 91 were female (33.5%), and 3 respondents selected the "other / prefer not to say" option (1.1%). In terms of age groups, the sample mainly consisted of younger and middle-aged fans: 60.7% belonged to the 1981–1999 age group, while 26.8% were born between 2000 and 2010.

The sample also showed strong long-term commitment to Formula 1. A total of 65.4% had followed the sport before 2010, while 17.3% started following it between 2017 and 2021, and 8.5% after 2022. This suggests that although the sample contains many respondents who are considered long-time fans, it also includes newer audiences who entered the world of Formula 1 during or after the rise of *Drive to Survive*. The intensity of race following was high: 82.7% reported watching every race live, while 7.7% only watched the most important races.

The strongest motivations for following Formula 1 were the excitement of racing (88.6%), attachment to drivers and teams (81.3%), and interest in technological development (50.7%). The prominent importance of drivers and teams is particularly significant because *Drive to Survive* is built around character-focused storytelling. Content preferences also support this pattern: 41.5% of respondents preferred behind-the-scenes content and interviews, while 28.7% preferred analytical content. This indicates strong audience interest in narrative and behind-the-scenes content.

The MSSC results showed that entertainment and experience-based motivations dominated. The highest-rated item was "*Formula 1 entertains and relaxes me*" ($M = 4.53$; $SD = 0.74$), followed by "*It is important for me to stay informed about what is happening in the sport*" ($M = 4.48$; $SD = 0.81$). Emotional involvement was also significant ($M = 4.02$; $SD = 1.03$), while the visual and technological aspects of the sport also played an important role ($M = 4.23$; $SD = 0.93$ and $M = 3.53$; $SD = 1.16$).

The SSIS results indicate a high level of fan identification. Respondents strongly agreed that they remain loyal to their favourite team even when it performs poorly ($M = 4.50$; $SD = 0.91$), and that they regularly follow Formula 1 events ($M = 4.57$; $SD = 0.79$). Emotional attachment to a favourite driver or team was also high ($M =$

4.08; SD = 1.11). However, active content sharing was less characteristic ($M = 2.78$; $SD = 1.48$), suggesting that many respondents participate as engaged but relatively passive digital consumers.

The DFES results further confirmed the importance of digital engagement. Following official Formula 1 social media channels reached an average of $M = 3.74$ ($SD = 1.27$), while the statement that social media content enhances the fan experience reached $M = 3.54$ ($SD = 1.13$). Overall, 60.3% of respondents stated that digital and social media content make them more engaged with Formula 1. In addition, 46.3% regularly and 37.5% occasionally follow the personal social media profiles of drivers or teams, suggesting that fan attachment is increasingly built around individual personalities and character-based narratives.

Finally, respondents clearly recognized the marketing and entertainment logic behind contemporary Formula 1. A total of 61.4% stated that marketing and entertainment play a decisive role in the development of the sport, while 34.6% considered them important but not dominant. This supports the interpretation that Formula 1 is increasingly perceived not only as a sport, but also as a media and entertainment product.

4.2 Qualitative Results

The 14 semi-structured expert interviews confirmed the patterns identified in the survey. One of the strongest recurring themes was the strategic transformation of Formula 1 following the Liberty Media acquisition. Interviewees emphasized that the sport shifted from a relatively closed and elite model toward a more open, digital, and entertainment-oriented media system. As one expert noted, Liberty Media “*started transforming Formula 1 into a global entertainment product.*”

Experts also highlighted that modern Formula 1 is no longer limited exclusively to race weekends. Instead, it operates as a continuous content ecosystem supported by social media, streaming platforms, F1 TV, behind-the-scenes content, and driver-focused communication. This supports the interpretation of Formula 1 as an “always-on” media product, where fan engagement is maintained throughout the season, not only during individual race weekends.

The interviews also emphasized the central role of *Drive to Survive*. Several experts argued that the series brought new audiences into the sport, particularly viewers who had not previously followed Formula 1. One interviewee stated that without *Drive to Survive*, it would be difficult to imagine three races being held in the United States. The series was repeatedly described as a turning point because it translated the technical and competitive world of Formula 1 into a more accessible format.

The key mechanism behind this effect was storytelling. Experts noted that the series foregrounds personal stories, rivalries, conflicts, and emotional moments instead of simply presenting race results. This approach strengthens the personal brands of

drivers and helps viewers develop emotional connections with individual personalities. This qualitative finding is consistent with the survey results, where 41.5% of respondents preferred behind-the-scenes content and 46.3% regularly followed the personal social media accounts of drivers or teams.

At the same time, the interviews provided a more nuanced interpretation. While most experts evaluated Formula 1's media transformation positively, some also noted that the growing entertainment orientation may create tension with the sport's traditional values.

4.3 Integration of Quantitative and Qualitative Findings

The quantitative and qualitative findings clearly reinforce each other. The survey results show that fans are highly engaged with Formula 1, strongly attached to drivers and teams, and increasingly influenced by digital media content. The expert interviews explain this pattern from an industry perspective, linking it to Liberty Media's strategy, the rise of streaming platforms, and the logic of *Drive to Survive*.

The most important connection between the two data sources is the role of character-based storytelling. Quantitatively, this appears in the high importance of attachment to drivers and teams (81.3%), the preference for behind-the-scenes content (41.5%), and the frequent following of drivers' or teams' personal social media profiles (46.3% regularly; 37.5% occasionally). In the qualitative research, experts described the same process as a shift toward personal narratives, emotional identification, and continuous digital content production.

Overall, the findings suggest that *Drive to Survive* acted as a catalyst in Formula 1's transformation into a global entertainment-oriented media brand. The series did not create this transformation on its own, but it made the sport more accessible, emotionally engaging, and visible to new and less specialized audiences. In this sense, Formula 1's recent growth can be interpreted as the result of the integration of sporting performance, digital storytelling, platform-based media consumption, and strategic sports marketing.

Conclusion

This study examined how the digital media environment, and particularly Netflix's *Drive to Survive* documentary series, contributed to the transformation of Formula 1's fan culture, media presence, and consumption habits. Using a mixed-methods approach, the research combined survey data from Formula 1 fans with expert interviews to gain a clear understanding of the sport's media and business transformation.

The findings show that Formula 1 has undergone significant changes from a traditional motorsport competition toward a complex media and entertainment product. The expert interviews identified Liberty Media's acquisition as a strategic

turning point, after which the sport's communication and marketing activities increasingly adapted to digital platforms, streaming services, and continuous content production.

The quantitative results support this interpretation. Respondents reported strong interest in digital and social media content, behind-the-scenes material, and driver- or team-centered narratives. This indicates that the Formula 1 fan experience is no longer limited to watching races but increasingly includes the continuous consumption of media content surrounding the sport.

The combination of the qualitative and quantitative findings highlights the specific role of *Drive to Survive*. The series contributed to Formula 1's growing popularity by making the sport more accessible to less specialized audiences and individuals less interested in sport through character-centered storytelling, personal rivalries, and emotional narratives. These elements helped transform Formula 1 from a technically complex motorsport into a more understandable and entertaining media brand, making it far more accessible and understandable for a wider audience.

The study contributes to the understanding of media-driven sports consumption by demonstrating how documentary series, streaming platforms, and digital storytelling can strengthen fan engagement and support audience expansion. From a practical perspective, the findings suggest that sports organizations should treat narrative content production and digital platform strategies as central elements of contemporary sports marketing.

However, the research also had limitations. The survey sample was limited in size and mainly drawn from online fan communities, which restricts generalizability. In addition, the qualitative findings are based on expert interviews and therefore provide a more interpretive than fully representative industry perspective. Future research should examine the long-term impact of streaming-based sports content on larger and more international samples and further investigate how character-centered storytelling influences fan identification in other sporting contexts.

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Turning Crisis into Opportunity: Tourism-Led Nation Branding in Türkiye

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Abstract: This paper focuses on the case of Türkiye, more specifically from the perspective of tourism-focused national brand. Our aim is to analyse the way in which tourism is a national recovery instrument of the Republic of Türkiye, given the economic crisis the country has been facing. Our methodology is qualitative, more specifically interpretative and analytical. We shall analyse the national branding and rebranding of the Republic of Türkiye. Throughout this paper, we will also focus on specific concepts, such as: “Made in Türkiye” and “Go Türkiye” as a means to promote heritage and tourism to both national and international tourists and attempt to analyse the country’s position and the background supported by cultural and public diplomacy, concentrating on the specificities of the Turkish national branding.

Keywords: Türkiye, national branding, tourism, economy, public diplomacy

1 Introduction

The Republic of Türkiye has been facing changes in its structure and profile, both internally and externally in its recent, modern history as a republic. These phenomena are explained by the rapid developments in the international community, leading to an acute need of adaptation through change. Moreover, a very important factor that fuelled the need of rebranding was the economic crisis, turning tourism into a national recovery strategy.

In the case of Türkiye, the process of rebranding represents an approach to the roots, in a nationalist trend. More specifically, the rebranding is meant to extend the internal profile of Türkiye internationally and promote the national identity and cultural specificities of Turks. When it comes to what “rebranding” actually means or stands for, we can address this term with the meaning of “repositioning” or “re-introducing” rather than “changing”. Therefore, in the case of Türkiye, the national rebranding does not imply adding new or external elements to the national image, but rather reshaping it and repositioning it in the international community; all these

elements are meant to send a message to both the internal and international *public* and *invite* them to perceive the country in a certain manner.

1.1 Motivation for the Paper. Objectives. Research Questions.

The motivation for this paper lies in the tight connection between the Turkish economy and the Turkish tourism; in other words, our objective is to present and analyse the Turkish tourism campaigns and diplomatic tools in the field of tourism as part of the national branding strategy in relation with their effect on the Turkish economy. Therefore, our research questions are:

1. What are the national rebranding strategies of the Republic of Türkiye in the field of tourism?
2. How can tourism represent a national recovery instrument of the Republic of Türkiye?

1.2 Turkish Economy: Economic Crisis & Tourism

One of the starting points relevant for our analysis is the year 2018, when the Turkish lira started to collapse. As compared to the American currency, the Turkish lira “lost 40 percent of its value”[1].

Another very important stalemate was the COVID-19 pandemic, where the global economy was highly affected. The Turkish Central Bank adopted some “unconventional” policies in 2019-2020, while in 2021, president Erdoğan’s policies (for example cutting interest rates, according to his belief that “high inflation is the outcome of high interest rates”[2]) did not really help the economic situation. In 2022, the inflation in Türkiye exceeded 80% and “Türkiye’s export rate to the European Union decreased from 43.1% to 40.5%” [3]. The elections in 2023 complicated the situation even more, but in a rather positive manner, due to the “tighter policy mix, focused on fiscal policy”; in other words, the new economic policies were getting more conventional, helping the Turkish economy overcome some of the more serious previous problems [4]. Currently, in 2026, the inflation is around 31% in March [5].

The tight rapport between tourism and Turkish economy is explained by the fact that tourism represents approximately 13% of Türkiye’s overall economy.

2 National Rebranding

2.1 Public Diplomacy

The launching of the Office of Public Diplomacy within the Prime Ministry in 2010 opened the way to a series of events concerning Turkish public diplomacy, an area that needed to be developed as a consequence of globalisation and regional developments [6]. “In Türkiye, public-diplomacy activities are conducted within two main frameworks: state-to public (explaining the state’s policies) and public-to-public (done with the employment of civil elements)’[6]. The public element is crucial, since it is very much related to the common sense: the Turkish perception about its own identity. The sick man of Europe needed to overcome the Sevres Syndrome.

When it comes to Turkish soft power, what is different from that of other countries, since it emerges from the cultural and historical inheritance, especially from the Ottoman Empire, that brought together many different diverse groups and facilitated intercultural dialogue [6]. Moreover, Turks see themselves as the heirs of the Ottoman Empire, therefore responsible for perpetuating and promoting the Ottoman heritage. This can be related to the above-mentioned Sevres Syndrome and the sick man of Europe: in the Ottoman period, Turks used to have great power, not only military, but also geopolitically, due to their expansion; later on, the Europeans started to modernise their internal infrastructures and Turks were no longer a reference point [7], making them want to return to the powerful international image they used to have – explaining why the currently use some aspects from the Ottoman period.

2.1.2. From Turkey to Türkiye. Turquality. National Brands

In 2021, the international denomination “Turkey” was replaced with Türkiye. Even though the English term might be associated with other meanings (such as the bird turkey, or the meaning failure or ignorant), there is also an ideological dimension attached to this change: along with patriotism or even nationalism, the message sent is that there is only one Türkiye (i.e. transparency) and “as opposed to other countries, it cannot be completely and fully internationalised”. Moreover, religious symbolism can also be traced: in Islam, the conversion requires receiving a new name; therefore, the Neo-Ottomanist doctrines and faith-based diplomacy practices can be tightly related to this change [8].

In the early 2000’s, the Ministry of Economy launched a branding program called “Turquality”, through which Turkish companies emerged and developed on the international global market by creating global brands for Turkish businesses [9]. A very important part of Turkish public diplomacy is the national brand “Türkiye: Discover the potential” along with “Made in Türkiye”.

The brand's name "*Turquality*" was not chosen by coincidence; when it comes to its meaning, we can understand that this formed term "*Turquality*" is a combination of "*Turkish*" and "*turquoise*", which in Turkish is referred to as "Turkish blue" (*Türk mavisi*). The stone with the same name was brought to Europe through Türkiye [10], becoming a representative colour for Turks.

Another relevant campaign was launched in 2022, under the name of "Hello Türkiye" and the slogan "Say Türkiye" [11]. A brief analysis shows that the use of these words is not by coincidence.

The meaning of these campaigns and slogans is to make the country accessible internationally – not only the use of English language, but also of internationally known and recognised short terms are highly important: they are easy to be remembered, politically neutral and hence, correct and correlated with places form the tourism strategies, like Istanbul or Kapadokya, usually known worldwide.

2.2 Potential for Paradiplomacy

To begin with, the concept paradiplomacy refers to the foreign-policy capacity of sub state entities and their participation in the international arena. The challenge intervenes when considering international law: sub-state entities are not considered to be subjects or actors of international relations, only states intrinsically [12]. Even so, sub-state entities only follow the national guidelines when it comes to policies and diplomacy in general, which makes the two act unitarily. One of the most important pillars of paradiplomacy can be considered to be *city diplomacy*.

2.3 Cultural and City diplomacy

In order to prove its flair for cultural diplomacy, we shall take a look at the city's capability in terms of city diplomacy – i.e. the connection and communication between cities (such as sister cities) but also, attracting foreign investments, promoting cultural values and shaping social connections between citizens [13]. Even though it is a form of sub-state diplomacy, it is a crucial "tool of the local government in promoting social cohesion, conflict prevention and the creation of a stable environment in which the citizens can live together" [9].

One of the most relevant campaigns in this field is entitled "Istanbul is the new cool", promoting the city from a double perspective: on one hand, for its historical heritage and on the other hand, for its modern face, described as "a thriving scene of arts, design and culture" [14]. What we can see, therefore, is the combination of numerous points of attraction in order to make this a very inclusive tourism strategy; in other words, this strategy aims to gather a large "public" to visit the city, either due to its historical and traditional background, or due to its modern and "*cool*" façade. The main rationale is the fact that Istanbul is considered to be the meeting

point of two continents, having a strategic position in the international arena. Additionally, as mentioned before, it is the biggest city of the country, thence it is crucial for it to be very well organised.

Conclusions. Perspectives

One of the most important aspects when it comes to the impact of tourism and national rebranding on economy is related to the power of the Turkish Lira in relation with other currencies. Even though for Turkish citizens it might be a burden in everyday life, for international tourists, it represents a stimulation to visit Türkiye, for it turns to be in their benefit to exchange their local currency (USD, Euro etc.) for Turkish lira's and afford much more than locals. Therefore, by becoming an affordable destination for foreigners, Türkiye can introduce itself and present its national and cultural heritage which turns tourism into a national branding strategy. The exchange that takes place is that several foreign tourists come and visit the country, while the national image travels abroad and expands over the borders, shaping the country's international image.

One of the most relevant aspects which results from the analysis of the tourism and national branding campaign is their duality: on one hand, Turks attempt an international exposure by using English words and recognised phrases (such as "Say Türkiye"), representing a memorable message; on the other hand, what they promote are very traditional places in terms of Turkishness, i.e. they promote their national identity and cultural heritage, creating a very *national-specific* brand of the country (starting from the international name "Türkiye"). In this way, they can preserve their specificities and transmit the idea of *uniqueness* to potential tourists, in the idea that even though Türkiye is an international destination, what you will see is rather Turkish than internationalised.

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From War to Cooperation: Crisis-Driven Innovation and Romania's Modernization Model

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Abstract: This paper examines European integration as a historically grounded response to systemic crises, with a particular focus on the transformative impact of war and economic disruptions. Rather than interpreting integration as a linear or inevitable process, the study highlights the role of crisis as a catalyst for institutional innovation, policy learning, and shifts in governance paradigms. By exploring how the trauma of the two World Wars reshaped political thinking, the research illustrates the transition from competition to interdependence through the supranational management of resources. Furthermore, the paper incorporates a case study focused on Romania (1989-2026), highlighting how the post-communist transition and recent shocks have been managed through the European Union's "External Anchor". Romania's experience demonstrates the conversion of structural vulnerabilities into opportunities for modernization, empirically evidenced by the leap in GDP per capita from 26% to over 80% of the EU average (with an estimated 83% in 2026) and its advancement to 23rd place globally in the Economic Complexity Index. Combining a macro-historical perspective with quantitative analysis, the paper argues that the European model represents a viable framework for adaptation applicable to contemporary challenges, contributing to debates on polycrisis management and the evolution of economic cooperation.

Keywords: European integration, systemic crisis, institutional innovation, Romania, external anchor, economic convergence.

1 Introduction

The economic history of the continent demonstrates that major systemic shocks act, in most cases, as the primary catalyst for institutional innovation. Although the post-war foundations of European integration were publicly legitimized through an appeal to the collective memory of conflict, the mechanism that ensured the project's actual survival was strictly economic. By placing strategic sectors under a

supranational authority, European states were compelled to abandon economic nationalism in favor of irreversible market interdependence [1]. Thus, common governance became a sophisticated instrument of resilience, capable of absorbing crises through spillover effects and continuous structural adaptation [2].

The absolute driver of this transformation at the regional level was the influx of a stock of Foreign Direct Investment (FDI) which currently exceeds the historical threshold of 100 billion euros. This mass of capital has completely restructured the domestic productive apparatus. In less than two decades, Romania has evolved from a transition economy based on cheap labor and primary textile exports into a diversified industrial force, climbing substantially in the *Atlas of Economic Complexity* produced by Harvard University to 23rd place globally in profile evaluations [3]. This technological sophistication is visible at the micro level through the development of high-performance industrial hubs, such as the automotive poles (Dacia-Renault in Mioveni and Ford Otosan in Craiova), which have generated extensive networks of local suppliers with high value-added [4]. In the same global complexity benchmark, positions immediately above are occupied by major innovative powers such as the United States (20th), France (21st), and Denmark (22nd) [3].

Paradoxically, although Romania is recognized as a high-income country, occupying 43rd place in a hierarchy of the wealthiest economies per capita out of 145 studied by the Harvard Growth Lab, its productive structure is much more complex than would be expected for its current income level [3]. However, aggregate convergence figures often mask severe internal discrepancies, a critical aspect that this analysis addresses head-on. That huge stock of foreign investment is disproportionately concentrated in the Bucharest-Ilfov area and in the western counties, leaving macro-regions like North-East or South-West vulnerable from a productive standpoint [5].

Furthermore, the economic architecture remains exposed to external shocks. The recent period of poly-crises (2022-2025) revealed serious macroeconomic fragilities: inflationary pressures exceeding the 15% threshold and concerning current account deficits, which constantly oscillate between 6% and 9% of GDP [6]. The fact that Romania operates under the restrictions of the Excessive Deficit Procedure (EDP) triggered by the European Commission underscores the limits of a growth model largely sustained by consumption [6]. Faced with these turbulences, state resilience was no longer based on conjunctural political interventions, but on independent economic instruments. The National Bank of Romania (BNR) provided a shield of stability through a strictly managed liquidity approach and a monetary policy interest rate maintained at 7%, protecting the purchasing power of the national currency [7].

Regarding investment, the National Recovery and Resilience Plan (PNRR), approved in its modified version by the EU Council in December 2023, injects 28.5

billion euros into infrastructure and structural reforms, of which 14.9 billion euros are allocated as loans and 13.6 billion euros as grants (including the REPowerEU package), conditioning each financial tranche on the implementation of substantive fiscal reforms [8]. This introduction sets the analytical framework of the paper: to overcome its status as an assembly economy and secure long-term convergence, Romania must transition from formal integration, based on legislative alignment, to internal structural resilience, characterized by technological innovation, budgetary discipline, and regional cohesion.

2 Research Questions and Methodology

To move beyond purely descriptive approaches and to dissect the structural dynamics of the convergence model, this research is guided by three fundamental questions:

1. To what extent has the "External Anchor" represented by the EU driven a qualitative mutation in the Romanian productive apparatus, moving beyond mere formal institutional compliance?
2. What is the actual impact of asymmetries in the territorial distribution of capital flows (FDI) on the widening of subnational economic disparities?
3. How has Romania's macro-monetary stabilization architecture interacted with the asymmetric shocks of the poly-crisis period (2022-2025), under the conditions of a chronic structural fiscal deficit?

Methodologically, this study is framed as an institutional political economy case study, employing a mixed qualitative-structural analysis. This conceptual lens was chosen over a purely linear quantitative econometric model because our primary objective is not to isolate a statistical regression function, but rather to dissect the behavioral mechanics of regulatory institutions during periods of systemic stress. To quantify structural transformation, the research utilizes a comparative analysis of real convergence indicators, specifically GDP per capita at Purchasing Power Parity (PPS), alongside industrial sophistication metrics sourced from the Harvard Growth Lab's Atlas of Economic Complexity. [3] The correlation between capital flows and convergence is evaluated by examining the evolution of the Foreign Direct Investment (FDI) stock as reported by the National Bank of Romania [7], cross-referenced with Eurostat data on regional asymmetries [5]. This methodology enables us to isolate microeconomic spillover effects (via case studies on industrial clusters) while simultaneously assessing macroeconomic vulnerabilities through the lens of the Excessive Deficit Procedure [6].

To validate the macroeconomic hypotheses and dissect the mechanisms through which European integration has generated structural transformations, this paper

analyzes two microeconomic case studies representative of Romania's coupling to global value chains: the industrial clusters of Mioveni (Dacia-Renault) and Craiova (Ford Otosan). These serve as units of analysis to observe how the transfer of technology and know-how from multinational corporations to the local supplier ecosystem has stimulated industrial convergence. At the same time, these case studies offer a critical perspective on the limits of indigenous innovation, demonstrating that while integration has been a success in terms of assembly and sophistication, the capacity to generate one's own value-added remains conditioned by R&D policies and the retention of highly skilled human capital.

3 The Case of Romania: Systemic Transition and the EU's "External Anchor"

Romania's post-communist transition serves as an ideal empirical laboratory for analyzing adaptive governance under the pressure of systemic crises. The collapse of the Council for Mutual Economic Assistance (COMECON) trade networks and the abrupt deindustrialization of the 1990s created a macroeconomic environment characterized by extreme volatility, hyperinflation, and institutional fragmentation. Within this context of structural vulnerability, the opening of EU accession negotiations (Helsinki, 1999) acted as a vital exogenous stabilization anchor [9].

From a theoretical perspective, the analytical bridge between post-1945 Western European resource management and Romania's post-1989 synchronization does not aim to identify similarities in raw industrial sectors. Rather, it operates strictly at the level of the mechanism of sovereignty transfer. In both cases, the forced adoption of exogenous governance rules, driven by the imperative of crisis survival, functioned as the sole vector capable of dissolving rigidities and resistance to reform within domestic state structures. The management of pre-accession programs (Phare, ISPA, SAPARD) imposed a strict procedural discipline, forcing the domestic bureaucracy to internalize rigorous standards of audit and fiscal transparency [10].

The effects of the EU's external anchor were not confined to the modernization of public institutions. The accession process also increased Romania's credibility in the eyes of international investors by reducing uncertainty and reinforcing expectations of long-term stability. Consequently, the institutional reforms required by European integration were accompanied by a substantial increase in Foreign Direct Investment, which became one of the main drivers of economic transformation.

3.1 Foreign Direct Investment and Industrial Complexity

The effects of the EU's external anchor extended far beyond administrative reform. As Romania moved closer to membership, the accession process increased the country's credibility in the eyes of international investors by reducing uncertainty and reinforcing expectations of long-term political and economic stability. The opening of accession negotiations in 2000 provided a clear roadmap for legislative and institutional modernization, while signaling Romania's future integration into the European Single Market.

As a result, the country experienced an unprecedented surge in Foreign Direct Investment (FDI). Between 2003 and 2008, annual FDI inflows increased from approximately USD 2.2 billion to a record USD 13.5 billion. This remarkable expansion was driven by the combination of EU-driven institutional reforms, an accelerated privatization process, and favorable international economic conditions. By 2008, Romania had become one of the most attractive destinations for foreign capital in Central and Eastern Europe, demonstrating how European conditionality could translate into tangible economic transformation [11].

The importance of this investment boom lies not only in its scale but also in its structural impact. A significant share of foreign investment was directed toward industry, contributing to technology transfer, productivity growth, export upgrading, and the integration of Romanian firms into European and global production networks. Foreign-owned companies introduced new managerial practices, modern technologies, and higher production standards, helping domestic suppliers become more competitive and accelerating the modernization of the productive sector. In this sense, FDI functioned as a catalyst for industrial upgrading rather than merely as a source of external financing.

The results of this transformation are clearly visible in Romania's position within the global economy. Over the course of two decades, the country evolved from a transition economy associated primarily with low-cost labor and labor-intensive exports into a far more diversified and technologically sophisticated manufacturing base [3]. This shift is reflected in Romania's steady rise in the Economic Complexity Index, which measures the diversity and sophistication of a country's productive capabilities.

This qualitative mutation is faithfully reflected in The Atlas of Economic Complexity, where the country has recorded a remarkable ascent, consolidating its position within the upper echelon of sophisticated economies [3]. Furthermore, the predictive power of this development model was documented as early as the seminal Boston-based research editions, where long-term growth projections placed Romania 16th globally and 6th in the Eastern Europe and Central Asia region regarding estimated GDP per capita dynamics for the 2009-2020 interval. This early performance was theoretically grounded precisely in the positive asymmetry

between the structural complexity already accumulated by the domestic productive apparatus (corresponding to 52nd place globally in 2009) and its level of monetization at that time. The predictive gap indicated that Romania possessed untapped technical know-how, capable of propelling the average income from 7,500 USD to a projected value of 10,823 USD by 2020, thus validating in advance the success of the real convergence model that followed [12].

A crucial methodological aspect, highlighted in the definitive data published by Harvard for the 2024 horizon, is the positive asymmetry between gross income levels and the country's technological capacity. While Romania ranks 43rd globally in terms of gross wealth per capita in profile evaluations, its structural performance from the perspective of the Economic Complexity Index (ECI) places it considerably higher, at 23rd worldwide [3].

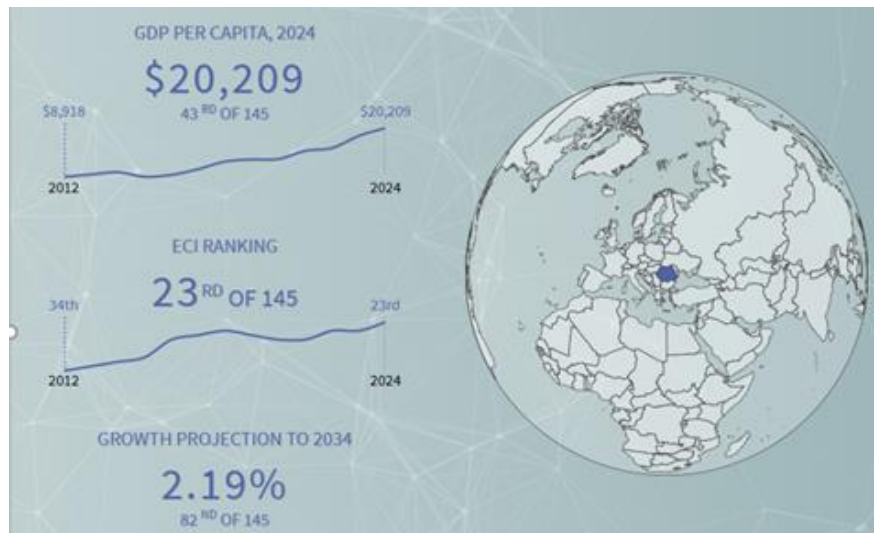


Figure 1

Harvard Growth Lab. Romania's Economic Complexity Profile, The Atlas of Economic Complexity, Harvard University, Boston, 2024
<https://atlas.hks.harvard.edu/countries/642>

This exceptional positioning places Romania in the immediate vicinity of frontier economies such as the United States (20th), France (21st), and Denmark (22nd), while also revealing a striking macroeconomic paradox: it net-surpasses Norway, which currently sits at 39th in the same global benchmark [3].

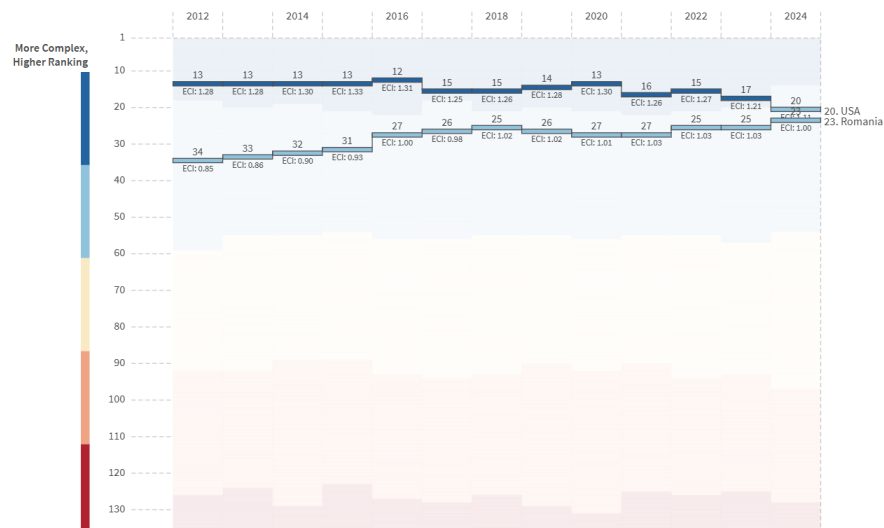


Figure 2
Complexity Rankings and Growth Projections
<https://atlas.hks.harvard.edu/rankings/>

At the micro-level, this technological sophistication is clearly visible in the density of high-performance domestic hubs - such as the automotive clusters in Mioveni (Dacia-Renault) and Craiova (Ford Otosan) - which are capable of vertically integrating extensive networks of local suppliers into high value-added processes [4]. However, this model reveals a major structural flaw: territorial distribution remains profoundly asymmetric. As highlighted in Figure 3, the massive concentration of capital within the Bucharest-Ilfov region and the technological hubs of the west leaves the country's geographical periphery in a state of productive isolation.

Development Region	Share of Total FDI Stock (%)	GDP per capita in PPS (% of EU average)
București - Ilfov	61.2%	> 160%
Vest (Timiș, Arad)	11.5%	85%
Centru (Brașov, Sibiu)	8.8%	78%
Nord-Est (Moldova)	3.1%	46%
Sud-Vest Oltenia	2.4%	51%

Table 1

Regional Distribution of FDI Stock and Regional GDP Gaps in Romania

Source: Synthesis based on National Bank of Romania (BNR) Regional FDI Reports [7] and Eurostat regional accounts data [5]. The table maps the severe spatial polarization of foreign capital, demonstrating a direct mathematical link between localized FDI concentration and subnational economic divergence [13].

National wage dynamics confirm deep-seated disparities across economic sectors, directly mirroring the hierarchy of economic complexity and the varying capacities to absorb high value-added investments. Data synthesized by the National Institute of Statistics in its Monthly Statistical Bulletin (No. 12/2025) [14] reveals a significant structural gap favoring advanced technological sectors in both gross and net average monthly earnings.

A comparative analysis of the Bulletin's indicators (Tables 47, 48) shows that net compensation in high-tech industrial branches - such as electronics manufacturing, computer production, and advanced automotive transport - consistently outperforms the industrial sector average. This wage premium, ranging between 25% and 35%, serves as more than just a proxy for sectoral profitability; it acts as a primary driver of regional economic divergence, effectively pulling highly skilled labor toward major industrial hubs and urban growth poles [14].

3.2 Real Convergence and Macroeconomic Vulnerabilities

At the aggregate level, closing the gap with the European Union average represents an undeniable success of this economic integration model. Historical data demonstrates a sharp acceleration in real convergence indicators, with Romania surpassing the 80% threshold of the EU average by 2026 [5]. Labor productivity per employed person has followed a similar trajectory, bolstered by the rapid digitalization of services and the aforementioned industrial sophistication [6].

This upward path has been accompanied by a profound reconfiguration of the country's financial status on the global stage. According to synthesis structural analyses issued by the World Bank, accumulated performance has allowed Romania - alongside a select group including Bulgaria, Panama, and Costa Rica - to officially reach high-income status. This marks a historic transition, with the country advancing from its previous classification as a “frontier market” to the higher tier of “emerging markets” between 2012 and 2025 [15].

Reference Year	GDP per capita in PPS (% of EU average)	Labor Productivity (% of EU average)	Current Account Deficit (% of GDP)	Structural Fiscal Deficit (% of GDP)
2000 (Start of negotiations)	26%	31%	-3.7%	-4.2%
2007 (Effective accession)	44%	49%	-13.4%	-2.9%
2023 (Post-pandemic)	78%	72%	-7.1%	-6.3%
2026 (Current estimates)	83%	79%	-6.8%	-5.9%

Table 2

Evolution of Core Macroeconomic Convergence Indicators (2000-2026)

Source: Constructed by the author using data from Eurostat (2026) [5], World Bank Macro Poverty Outlook [6], and IMF Country Reports [16]. The operational metrics track the core paradox of the Romanian model: a spectacular catch-up process occurring simultaneously with the accumulation of internal and external macroeconomic imbalances.

This spectacular convergence trajectory, however, masks the buildup of chronic macroeconomic vulnerabilities typical of a small, open economy heavily reliant on external financial cycles [6]. The "twin deficits" - manifested by a persistent structural fiscal deficit coupled with a significant current account shortfall consistently oscillating between 6% and 9% of GDP - place Romania in a precarious position regarding capital market volatility [16]. Remaining under the Excessive Deficit Procedure (EDP) reflects severe budgetary rigidity, where current state expenditures leave extremely limited fiscal space for public investment financed from national funds [6].

During the recent poly-crisis period (2022-2025), characterized by asymmetric shocks to energy supply chains and an inflationary spike exceeding 15%, Romania's macroeconomic resilience was tested to its limits [6]. In this crisis scenario, stabilization did not emerge from pro-cyclical fiscal policies, but rather from an

autonomous institution: the National Bank of Romania. As a case study in micro-monetary adaptive governance, the NBR implemented a rigorous strategy to counter exogenous shocks. By finely tuning liquidity management in the interbank market and firmly raising the key policy rate to 7%, the central bank succeeded in anchoring inflation expectations and stabilizing the leu's exchange rate, thereby preventing a massive capital outflow [7]. This institutional shield provided the necessary breathing room for structural funds from the multiannual financial framework and PNRR injections - a 28.5 billion euro allocation approved in December 2023, structured into specific loans and grants - to begin restructuring the real economy, while conditioning further funding on the implementation of fiscal sustainability reforms [8].

3.3 Integration into Global Value Chains and Analysis of Complexity Indicators (2025-2026)

To understand the depth of this substantial integration, beyond the classical indicators of nominal convergence, it is imperative to dissect how the domestic productive apparatus has coupled with global value chains (GVCs). A landmark analysis published in the structural assessment reports issued by PwC Romania indicates that the country's accelerated rise in the Global Economic Complexity Index has been the primary vector that enabled it to surpass the critical threshold of 80% of the European Union's average GDP per capita [17]. This sophistication is not an abstract phenomenon; the performance is directly attributable to the development of high value-added industries. From this perspective, the production of industrial equipment, the manufacturing of high-power electrical transformers, and the development of the precision electronics segment have fundamentally reconfigured the profile of Romanian exports [17].

The qualitative shift from the traditional model, once based on low-wage labor, toward advanced manufacturing is further confirmed by operational data from the National Institute of Statistics (INS). According to official statistics, net wage earnings in high-tech sectors - with a particular focus on the pharmaceutical industry and the production of advanced automotive components - are 25-35% higher than the average recorded across the entire national industrial sector. This wage gap demonstrates the maturation of the labor market and the capacity of growth poles to attract highly skilled workers, thereby solidifying the transition toward substantive integration [14].

The OECD Economic Survey for Romania reinforces this paradigm, highlighting a convergence in income and productivity driven by profound structural reforms [18]. The implementation of projects financed through the National Recovery and Resilience Plan (PNRR) has acted as the primary growth engine, partially offsetting global economic uncertainties and transforming structural vulnerabilities into a

regional competitive advantage [8]. This structural resilience has been underpinned by a robust financial system; official data from the Financial Stability Report published by the National Bank of Romania demonstrates that the banking sector's performance and the prudential standards implemented by the NBR have served as an effective shield against global shocks [7].

However, it must be emphasized, as a note of analytical caution, that the convergence target estimated at 83% for the end of the 2026 fiscal year represents a baseline scenario contingent upon the stability of the regional geopolitical context. The latest OECD macroeconomic report (2026) indicates a temporary slowdown in real GDP growth in the short term, burdened by sovereign debt risks and domestic wage pressures [18]. Therefore, the 83% figure should be decoded not as a mathematical certainty, but as a projection strictly conditional upon the maintenance of the European security architecture and the acceleration of the effective absorption rate of PNRR funds before the August 2026 deadline [8]. Furthermore, an inherent limitation of the "External Anchor" model lies in its heavy reliance on the decisions of multinational corporations managing FDI flows in key technological sectors [4].

Currently, aggregate data do not precisely quantify what percentage of net value-added remains stored within the local economy to autonomously finance domestic research and development (R&D) programs. Future research will need to monitor the spillover effect on local SMEs to determine whether Romania is transitioning toward an indigenous innovation model or will retain the status of a "satellite" economy - albeit a high-tech one - within global supply networks.

3.4 Critical Discussions on the Sustainability of the Romanian Convergence Model

A rigorous scientific evaluation of Romania's post-communist trajectory requires abandoning exclusively triumphalist narratives in favor of a head-on analysis of the systemic vulnerabilities that jeopardize the long-term sustainability of convergence. In academic literature focused on Central and Eastern Europe, the economic model adopted by Romania is often conceptualized as a "dependent market economy" [19]. This structural paradigm reveals that while exogenous anchoring in European Union rules has ensured a massive infusion of capital, it has simultaneously generated a tactical subordination to the macro-strategic decisions of multinational corporations. The primary weakness of this mechanism lies in the risk of being caught in the "middle-income trap" - a plateau phase in which an economy loses its competitive advantages based on low labor costs, yet lacks the internal technological maturity to encompass or compete directly with economies based on pure innovation [20]. In this complex structural context, the fundamental question dominating current macroeconomic debates is whether this regional model centered

on massive FDI inflows can still evolve toward a new qualitative chapter of development, or whether its systemic rigidities irreversibly block the transition to frontier industries based on indigenous innovation [4].

A chronic barrier to economic autonomy is the systemic underfunding of the Research and Development (R&D) sector. With a consolidated budget allocation that has historically hovered below the 0.5% of GDP threshold (far below the 3% strategic target set by the European agenda) Romania fails to internalize and multiply the value added by foreign investors, officially earning it the label of a "modest innovator" in EU scoreboard evaluations [21]. The cutting-edge technology operated within the automotive clusters in Mioveni or Craiova is, in essence, imported know-how, while the domestic capacity to generate local industrial patents remains extremely limited. This structural gap turns real convergence into an asymmetric process: the country is rapidly closing the gap in terms of consumption and GDP per capita, yet it maintains a subordinate position within global value chains, functioning primarily as a provider of highly skilled, yet outsourced, technical labor.

These structural rigidities are compounded by a profound demographic crisis, structurally amplified by the phenomenon of international labor migration (brain drain) [22]. The loss of a significant share of the active human capital, particularly from segments with tertiary education and advanced technical qualifications, places severe pressure on the sustainability of social protection systems and limits the expansion capacity of regional industrial hubs. Thus, in the absence of aggressive public policies to stimulate indigenous innovation and correct the fiscal asymmetries of the Excessive Deficit Procedure, the Romanian model risks burning through the historical fuel provided by the first phase of integration, remaining trapped in the role of a satellite economy with fragile resilience against future asymmetric global shocks.

The Social Limits of Convergence

Despite these important achievements, economic convergence has not fully translated into social and territorial equality. Romania has experienced strong economic growth since joining the European Union, but significant inequalities remain. In 2023, Romania's Gini coefficient was around 32, above the EU average of approximately 30, indicating that the benefits of economic growth and European integration have not been equally shared among all regions and social groups.

Regional disparities remain one of the country's major challenges. Rural areas continue to be among the most vulnerable parts of Romania, representing around half of the population and facing greater difficulties in access to infrastructure, healthcare, education, and public services. The North-East region is one of the clearest examples of this imbalance, with a GDP per capita level of only around

47% of the EU average in 2023, making it one of the least developed regions in the country.

At the same time, Bucharest-Ilfov has developed at a very different pace, reaching around 190% of the EU average in GDP per capita in 2023. This contrast illustrates that economic modernization has not benefited all parts of Romania equally. While some regions have become strongly integrated into European economic networks, others continue to face structural disadvantages. Romania's experience therefore shows that economic convergence has advanced significantly, but social and territorial convergence remains an ongoing challenge. [23]

4 Key Macroeconomic Insights for Managing the Poly-crisis

The historical arc stretching from the economic ruins of 1945 to the accelerated real convergence trajectory of modern Romania provides an essential analytical framework for navigating the "poly-crisis" of the 21st century. Looking at these two timelines together reveals that regional integration is far more than a bureaucratic or legal formality; it functions as a structural survival strategy capable of turning systemic trauma into institutional resilience. The facts suggest that periods of linear stability often breed administrative inertia, while large-scale crises serve the vital purpose of forcing a radical rethink of economic power dynamics.

In the postwar era, the failure of nation-states to prevent total conflict led Jean Monnet to design a "solidarity de facto" that bypassed traditional diplomacy in favor of technical market integration [2]. In an isomorphic fashion, the collapse of Romania's communist state apparatus in 1989 created an institutional vacuum that could only be filled through the accelerated adoption of the Western European governance model [9]. The latest OECD Economic Survey for Romania confirms this mechanism: recent security and energy shocks acted as "burning platforms" that forced the digitalization of the administration and accelerated the green transition, effectively turning systemic disruption into raw material for a new developmental phase [18].

This dynamic highlights the value of innovation and institutional creativity. If the establishment of the European Coal and Steel Community (ECSC) in 1951 represented a pioneering exercise by placing strategic military resources under independent supranational control [24], Romania replicated this functionalist logic during its pre-accession period. A critical role was played by the use of Phare, ISPA, and SAPARD programs intended for structural alignment; the Romanian state did not merely engage in opportunistic financial absorption, but was compelled to build autonomous implementation agencies and transparent oversight structures [10].

These new administrative architectures proved flexible enough to absorb subsequent shocks, yet rigid enough to prevent a slide back into old, inefficient bureaucratic reflexes.

Shifting from a purely reactive logic of short-term survival to a long-term macroeconomic strategy remains the most complex psychological mutation. Post-war leaders like Konrad Adenauer and Robert Schuman refused to remain fixated on managing the legacy of the past, choosing instead to build a structure of peace based on interconnected markets [25]. Similarly, by embracing the EU's "External Anchor", policymakers in Bucharest enacted a historic reorientation of economic mindset, shifting focus from subsidizing inefficient, energy-intensive industries toward a multi-decade trajectory of real convergence [9]. This lesson remains valid in the current context: managing today's major challenges, from climate change to supply chain vulnerabilities, critically depends on the capacity of states to prioritize collective macro-structural stability over immediate nationalist or political gains.

Securing the legitimacy of such painful reforms necessitates a powerful public narrative, one deeply anchored in collective memory [26]. While in Western Europe the trauma of war and the ordeal of the Blitz provided the "moral mandate" for the historic ceding of sovereignty to supranational bodies [1], in the Romanian context, the symbolic project of "returning to Europe" served as the primary social glue, legitimizing the harsh economic restructurings of the transition period [9].

Ultimately, this evolution validates the success of adaptive governance. European integration did not manifest as a "Big Bang" event, but rather as a succession of incremental experiments based on the principle of learning by doing -a trajectory starting from the technical details of the *acquis communautaire* and culminating in the current execution of PNRR programs [8]. The flexibility of this institutional design allows economic systems to bend under the pressure of crises without collapsing. However, as highlighted by specialized reports issued by the OECD in 2026, maintaining this advantage requires a substantive shift: moving beyond the phase of mere legislative compliance and focusing massively on the development of human capital and indigenous technological capabilities [18]. Only through the qualitative internalization of these structural levers can Romania complete the transition from a position of passive conformity to that of an active, sovereign participant and a generator of high added value within global economic networks.

Conclusions

The present research argues that the European integration model operates fundamentally as a dynamic strategy for macroeconomic crisis management, capable of converting structural vulnerabilities into competitive advantages through an external institutional anchor. The economic leap achieved by Romania in just two and a half decades - from a peripheral level of 26% of the EU average GDP per

capita in 2000 to an estimated 83% by the horizon of 2026 - constitutes strong empirical evidence supporting the viability of this convergence mechanism [5]. The formation of a massive stock of Foreign Direct Investment, exceeding the historic threshold of 100 billion euros, alongside the country's sharp ascent to 23rd place in the Global Economic Complexity Index, confirms a profound qualitative mutation: the transition from an economy based on the exploitation of cheap labor to an industrial system superiorly integrated within transnational value chains [3] [4].

The conceptual novelty and original added value of this work reside in articulating a unique analytical bridge between post-war functionalist historiography and contemporary quantitative macroeconomic mechanisms. Unlike traditional approaches in the literature, which treat European integration either as a purely political project or as a linear succession of trade indicators, this study suggests the existence of a functional isomorphism between the institutional solutions of 1945 and current strategies for adapting to the global poly-crisis [2] [18]. By using the Economic Complexity Index (ECI) as a tool to validate institutional resilience, this research offers a fresh perspective on how an exogenous "external anchor" can force the internal restructuring of a productive apparatus stuck in transition asymmetries, providing a conceptual framework that may be applicable to other emerging economies currently undergoing regional integration [3].

However, this remarkable trajectory of aggregate convergence masks an internal structural duality and deep systemic vulnerabilities that cannot be ignored. The extreme spatial polarization of foreign capital, disproportionately concentrated in the Bucharest-Ilfov region to the detriment of peripheral macro-regions such as the North-East or South-West, indicates that the penetration of the modernization model remains partial and heavily fragmented within specific growth poles [5]. The overall assessment of these asymmetries shows that the regional development model exposes the state to the strategic decisions of transnational capital, risking captivity in structural bottlenecks if the transformations do not advance to the higher level of indigenous innovation [19] [20].

Furthermore, the persistence of the "twin deficits" underscores the limitations of a growth model fueled excessively by consumption and artificially sustained through exogenous financial injections [6]. This fragility is directly correlated with the chronic underfunding of the R&D sector (below 0.5% of GDP), which keeps the economy in the stage of a "modest innovator" reliant on subcontracting (outsourcing), while the exodus of highly skilled human capital (brain drain) limits the capacity for long-term autonomous recovery [21] [22]. To secure the sustainability of convergence beyond the advanced year of 2026, Romania will need to evolve from the phase of formal, administrative integration toward one of substantive integration.

Nevertheless, the findings presented in this study should be interpreted with a degree of analytical caution. While the evidence strongly suggests that European

integration and the EU's external anchor have played a decisive role in Romania's modernization trajectory, the relationship between integration and convergence cannot be reduced to a simple causal mechanism. Romania's economic transformation has also been shaped by broader regional dynamics, global capital flows, domestic policy choices, and the evolving structure of international value chains. Furthermore, indicators such as the Economic Complexity Index, although valuable in capturing the sophistication of productive capabilities, do not fully account for institutional quality, innovation capacity, social cohesion, or the territorial distribution of development gains. Future comparative research involving other Central and Eastern European member states could provide a more robust assessment of the specific contribution of European integration to long-term convergence and resilience. Such an approach would help distinguish between factors common to the region and those that are uniquely associated with Romania's development path.

From the perspective of public policy recommendations, correcting the territorial fractures highlighted in Table 1 requires an urgent reallocation of structural funds from the next multiannual financial framework toward major rapid-connectivity infrastructure projects (trans-regional highways) dedicated exclusively to the North-East and South-West macro-regions. Only by eliminating geographic logistical barriers can a natural decentralization of future FDI flows be stimulated, transforming local clusters from mere peripheral assembly points into indigenous high-tech industrial hubs. Strategically, these infrastructure measures must be mandatorily coupled with aggressive fiscal policies to incentivize private research activities, a planned increase in the public R&D budget toward the EU average, and the creation of robust institutional mechanisms for retaining technical talent. Only through this paradigm shift can Romania ensure its transformation from a satellite economy with fragile resilience into an active, sovereign participant with high added value within the global market.

In this sense, Romania should be viewed not as a definitive success story, but as an ongoing experiment in crisis-driven adaptation whose long-term sustainability will depend on its capacity to move beyond externally supported convergence toward innovation-led and institutionally embedded endogenous development.

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