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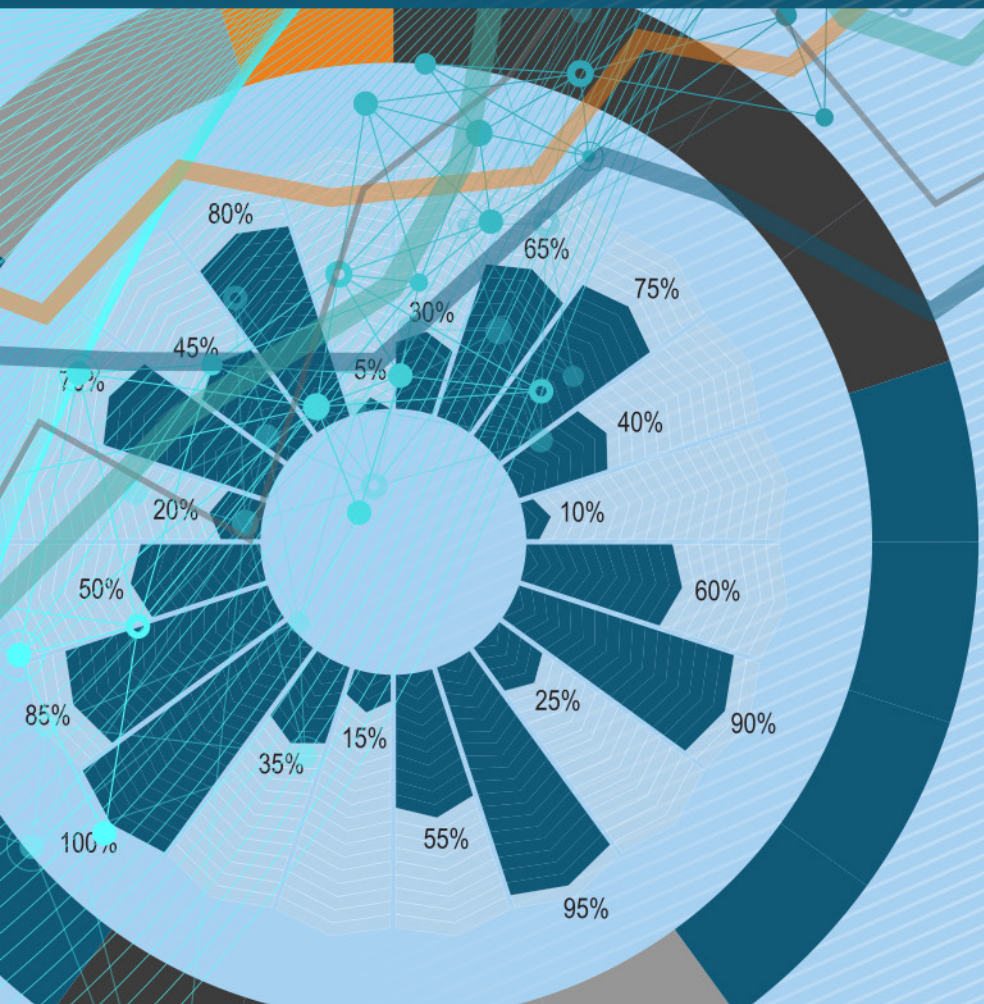

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Contents

Vietnam's economic growth in the age of digital transformation: opportunities and challenges

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ORIGINAL ARTICLE

Abstract. Vietnam is one of the leading countries in Southeast Asia in the digital transformation process and is among the developing countries that face both opportunities and challenges associated with this change. This research examines Vietnam's digital transformation owing to the country's quick adoption of new technologies and the pressing requirement to solve related structural limitations. Key prospects are examined, including innovation-driven development and global market integration, while facing issues including the digital divide, cybersecurity flaws, and possible economic displacement. This study uses a mixed-method approach, analyzing qualitative information from case studies and policy evaluations in addition to quantitative data from national and international official sources. The results highlight Vietnam's capacity to use digital transformation for sustainable and equitable growth while pointing out important areas that need attention. Creating strong digital regulations, encouraging collaborations between the public and business sectors, and expanding digital literacy initiatives are some examples of practical suggestions.

Keywords: digital transformation; economic development; Vietnam's economic growth; global integration; regulatory reforms; cybersecurity

JEL codes: O10, O14

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Introduction

Vietnam's vibrant economy and youthful, tech-savvy population exemplify a developing nation emerging from the challenges of the digital age. The country has purposely taken advantage of both the demographic dividend and its thriving innovation ecosystem, thus becoming a central digital player in Southeast Asia. The ICT sector contributed over 60% of the digital economy in Vietnam and raised around 16.5% of the GDP in 2023[1]. This above-average performance is due to the concentrated efforts of the Vietnamese government in propelling digital transformation, inducing technology-driven policies, and generating technology-related foreign investment. The rapidly growing e-commerce platforms and growing accessibility of mobile internet also add credence to Vietnam's digital economy.

Vietnam's digital economy has been established as the fastest-growing in Southeast Asia for the last two consecutive years, growing at impressive rates of 28% in 2022 and 19% in 2023 – again, three times faster than GDP[2]. This supercharged growth is demonstration of Vietnam's proactive transition into digital transformation and expanding powers in forming the region's technology-centric future. The developments show how quickly digital technology is being adopted.

Nevertheless, Vietnam stands, in all its might, against obstacles that hindering digital transformation: the capability to engage, accommodate those digital changes, and then introduce adjustments during and

[1] *The next wave of Vietnam's digital economy. Source: https://vneconomy.vn/techconnect//lan-song-tiep-theo-cua-kinh-te-so-viet-nam.htm (accessed on 15.03.2025)*

[2] *Digital economy expected to reach 18.6 per cent of Vietnam's GDP. Source: https://vietnamnet.vn/en/digital-economy-expected-to-reach-18-6-per-cent-of-vietnam-s-gdp-2342337 (accessed on 25.03.2025)*

after that. Even if for decades there have been educational reiterations around the expanded ownership of economic abilities and skill sets, these remain basically aligned to today's preponderantly «heavy» realities[3]. Limited capabilities in labor and the national economy create a differentiation for Vietnam in its transition behaviors that can provide varying challenges and constraints.

The aims of the study are to gain an accurate understanding of the relationship between digital transformation and economic growth in Vietnam. It discusses the progress made on the road to the use of digital technologies in the country, highlights impediments levelling growth, and provides some recommendations to overcome these impediments in a successful manner. The research adds to the ground-breaking discussion about the power of digital transformation in achieving sustainable development goals in developing countries, as is the case of Vietnam.

Literature Review

In recent decades, the idea of digital transformation has drawn a lot of interest, especially because of its potential to reshape economies, stimulate innovation, and improve competitiveness globally [12; 1; 17]. Business models and working environment have changed as a result of the COVID-19 pandemic, and digital technologies are essential for facilitating resilience and flexibility [16; 18]. Under these circumstances, in order to continue corporate operations and guarantee sustainable production and consumption practices, institutions should help firms by improving their resources and capacities, allowing them to embrace digital transformation [2]. Additionally, to ensure the successful implementation and long-term sustainability of digital transformation, it is essential to adopt developing techniques and tactics that can effectively guide and manage its complexity [11; 3].

In emerging economies, entrepreneurship and digital transformation, particularly blockchain, can accelerate economic development and promote innovation and expansion [4]. Furthermore, by changing the way capabilities are developed and improving learning opportunities for the workforce, digital transformation has an influence on numerous aspects of life, especially in human resources through higher education [14]. However, although digital transformation is quickly gaining popularity and offers many benefits and opportunities, it also comes with a number of drawbacks, especially for slower and developing nations [8]. Therefore, in developing nations like South Africa, the 4.0 Industrial Revolution will only succeed if governmental, corporate, and social leaders work together [13].

In Vietnam, digital transformation is a crucial driver of socioeconomic growth since it increases productivity, competitiveness, and innovation in a number of economic sectors [6; 5; 15]. Together with green investment and financial development, digital transformation may significantly improve the sustainability of Vietnam's existing high rates of economic growth [10]. For the cultural industry, digital transformation and entrepreneurship present new possibilities, skills, and difficulties that will change how it operates and foster an environment that is conducive to the expansion and advancement of Vietnamese culture [20]. Human capital, digital transformation, and startup success are strongly correlated. In Vietnam, entrepreneurs use human capital development to promote digital transformation, which improves company performance [7].

Although Vietnam is making progress and recognizes the significance of the digital revolution, it still has obstacles that must be overcome if it is to reach its full potential [22]. The differences of preparedness for digital transformation among Vietnamese businesses underscores the necessity of improving labor potential and economic and environmental efficiency to guarantee long-term company success [9]. Major obstacle facing Vietnam in the process of digital transformation, especially in logistics companies, is the lack of knowledge among management, the skills of the workforce, and the high implementation costs [21]. Additionally, the successful adoption and integration of digital technology is hindered by a number of obstacles, including governmental limitations like outdated regulations and inconsistent application [19].

The literature on digital transformation in developing nations, including Vietnam, emphasizes the potential as well as the difficulties that these nations confront. Although Vietnam has made great progress in embracing digital technology, it is stressed that a comprehensive strategy is required to overcome structural

[3] *Challenges and opportunities in Việt Nam's digital transformation process. Source: https://vietnamnews.vn/opinion/1687242/challenges-and-opportunities-in-viet-nam-s-digital-transformation-process.html# (accessed on 28.03.2025)*

obstacles. The foundation for comprehending Vietnam's distinct digital transformation journey is laid out in this review, which also provides insights for building strategies and policies in other developing countries. This study adds to the conversation on how digitalization might support fair and sustainable growth in developing countries by placing Vietnam in a global perspective.

Main Part

The digital transformation process in Vietnam

In the past three decades, Vietnam's economy has transitioned from a centrally planned economy to a vibrant market economy. Country has recorded an average GDP growth of 6.3% from 2000-2024, making Vietnam one of the fastest growing economies globally. Vietnam continued to develop positively during the COVID-19 pandemic where the economy posted a GDP growth of 2.9% in 2020, one of the highest rates worldwide during the pandemic. As per IMF, Vietnam's economy will continue growing rapidly to produce the highest economic growth of any emerging country in Southeast Asia with an acceleration of growth of 6.8% in 2025[4]. This rapid economic growth illustrates the growing economic foundations in Vietnam, as well as its key role in the overall development of the region.

From 2013 to 2023, Vietnam emerged as one of the nations with the quickest rates of growth in the Global Innovation Index (GII). In 2013, Vietnam came in at number 76 on this list. In 2023, ten years later, the country has climbed to 46th rank, securing a spot among the top 50 nations. Out of the 37 lower-middle-income countries, Vietnam's economy is now the second most creative[5]. A strong network of both local and foreign venture capital activity is estimated to boost the valuation of startups in Vietnam to close to $2 billion in 2022. There are over 3,800 startups in the nation, 11 of which are worth more than $100 million. Vietnam also has 100 startup incubators and 200 venture capital companies, which together support the country's expanding entrepreneurial environment[6].

This dynamic innovation landscape has been accompanied by significant digital economic growth, particularly in terms of its contribution to the national GDP (Table 1).

Table 1 – The added value contribution of the digital economy to GDP (2020-2023)

Sector	2020	2021	2022	2023	2024
Total	12.66	12.87	12.83	12.87	13,17
Agriculture, Forestry, and Fisheries	0.05	0.05	0.05	0.06	0.06
Industry and Construction	6.08	6.22	5.90	5.81	5.96
Services	6.53	6.6	6.88	7.00	7.15

Source: General Statistics Office of Vietnam, 2020-2024[7]

It is demonstrated that the services sector led and grew sustainably, reaching from 6.53 to 7.15% in 2024, while the overall contribution of the digital economy reached more than 13% of the national GDP. Over the years, the agricultural, forestry, and fisheries sectors stayed extremely small at 0.05-0.06%. In contrast, the building and industry sectors saw a slight decline, from 6.08% in 2020 to 5.96% in 2023. This trend highlights

[4] *International Monetary Fund. 2025. World Economic Outlook: A Critical Juncture amid Policy Shifts. Washington, DC. April. Source: https://www.imf.org/en/Publications/WEO/Issues/2025/04/22/world-economic-outlook-april-2025 (accessed on 22.03.2025)*

[5] *Global Innovation Index 2023 Innovation in the face of uncertainty 16th Edition. Source: hhttps://www.wipo.int/documents/d/global-innovation-index/docs-en-wipo-pub-2000-2023-en-main-report-global-innovation-index-2023-16th-edition.pdf (accessed on 22.03.2025)*

[6] *Digital economy accounts for over 18% of Viet Nam's GDP. Source: https://en.baochinhphu.vn/digital-economy-accounts-for-over-18-of-viet-nams-gdp-111240719131501058.htm# (accessed on 15.02.2025)*

[7] *General Statistics Office of Vietnam. Source: https://www.gso.gov.vn/tin-tuc-thong-ke/2025/01/thong-cao-bao-chi-ket-qua-bien-soan-chi-tieu-ty-trong-gia-tri-tang-them-cua-kinh-te-so-trong-gdp-grdp-giai-doan-2020-2024/ (accessed on 17.02.2025)*

the services sector's critical role in digital transformation and suggests ways to increase digital adoption across other industries.

Among the key components of the digital economy, e-commerce has emerged as a particularly dynamic and influential driver, reflecting broader changes in consumer behavior and digital business models in Vietnam (Figure 1).

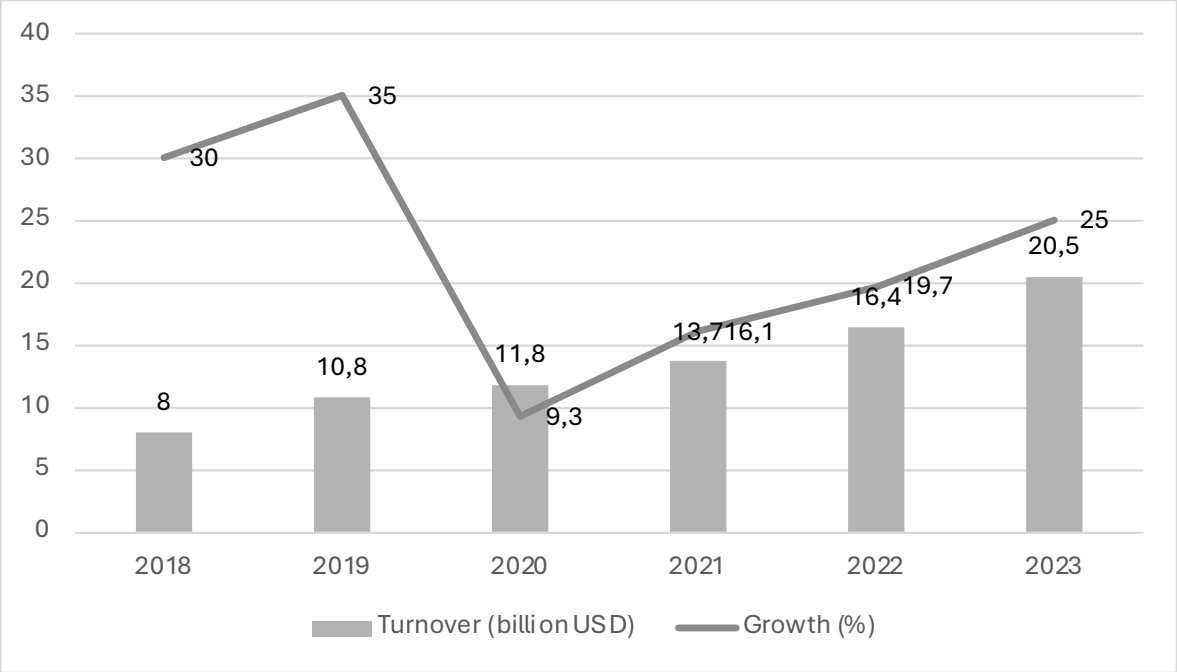

Figure 1. E-commerce retail over the years of Vietnam

Source: E-Commerce and Digital Economy Agency, 2018-2023

The turnover grew from $8 billion in 2018 to $20.5 billion in 2023. This rise in turnover is consistent with a trend of growing consumer use in seeking out online platforms for shopping. However, there is a degree of fluctuation to the rate of increase. The increase in turnover peaked at 35% in 2019 before falling significantly to 9.3% in 2020, potentially as a result of market corrections and disruptions due to the COVID-19 pandemic. The recovery that followed highlights the flexibility and ingenuity of the sector and growth was anticipated to recover to 25% in 2023. The steady growth illustrates the change in e-commerce use in retail environments and consumer behavior, confirming its essential position in today's economy. By 2023 Shopee, Lazada, Tiki, TikTok Shop and Sendo had established themselves as the leaders in e-commerce in Vietnam, delivering 2.2 billion products and achieving turnovers of USD 9.52 billion – which represents a 53.4% increase over the previous year. These players have increased their market share from 31.4% in 2021 to 46.5% in 2023, with expectations set to have revenues of USD 12.72 billion in 2024 – a 35% increase over the previous year[8]. This change illustrates Vietnam's creativity while also representing a culture increasingly depending on digital solutions to enhance connectivity, efficiency, and convenience. This combination of economic and societal digitalization bolsters the country's technology ecology, establishing it as a leader in sustainable growth in the digital age.

Vietnam is increasingly positioning itself as a new technological hub in Southeast Asia, thanks to the country's ongoing digital transformation, a developing startup ecosystem, and substantial venture capital investment (Table 2). This transformation has yielded advances in multiple sectors, establishing Vietnam as a major player in the Southeast Asian technology landscape. Initiatives by the government to promote this growth include forming innovation centers for cooperation and pooling resources, providing strategic support to digital entrepreneurs. These initiatives have also generated an eco-system that encourages business activity, which has attracted significant foreign and local investment.

[8] *Vietnam's E-Commerce Revolution: Telecom Infrastructure Paves the Way. Source: https://www.telecomreviewasia.com/news/featured-articles/4378-vietnam-s-e-commerce-revolution-telecom-infrastructure-paves-the-way/ (accessed on 21.03.2025)*

Table 2 – Overview of digital transformation in Vietnam by sector

Sector	Key digital transformation initiatives
Healthcare	Remote healthcare platforms, universal electronic medical records, telemedicine deployment in all healthcare facilities, creation of a national health database, smart hospitals
Education	Distance learning platforms have digitized curricula, with 100% of educational institutions implementing distance teaching and learning, online assessments, and updating university curricula on digital technologies such as AI and IoT
Finance & Banking	Digital banking services, automated processes, mobile payments, collaborations with FinTech for financial inclusion, and digital credit scoring systems
Agriculture	Smart agriculture, big data in farming, digital supply chain management, and initiatives like «Every farmer is a trader»
Transportation & Logistics	In order to modernize logistics, integrate seaports, rail, and warehousing, intelligent transportation systems concentrate on urban networks, highways, and digital platforms that facilitate digital profiles and efficient administrative procedures while optimizing transport management
Energy	Smart grid automation, digital meters, efficient energy distribution and loss detection systems
Environment	Comprehensive databases on managing resources, land, biodiversity, climate, and disasters, early warning systems, and open national digital maps
Industrial Production	Building smart factories, enabling intelligent operations, developing smart strategies and organizational structures, generating smart goods, and improving workforce digital skills are the main pillars of industrial manufacturing's digital transformation

Source: Authors

Through intentional efforts to implement modern technology across many sectors, Vietnam has made significant progress toward establishing a digital economy. The nation aims to increase accessibility, streamline operations, and improve service delivery by utilizing advances like big data, artificial intelligence (AI), and the Internet of Things (IoT). For example, the use of electronic medical records and telemedicine in the healthcare industry has improved systemic efficiency and lowered treatment obstacles. In the same way, educational programs aim to create a friendly environment, encourage lifelong learning.

Vietnam's comprehensive approach to addressing sector-specific issues and promoting sustainable development is shown in the incorporation of digital technology into industries including energy, transportation, and agriculture. Transparency and operational efficiency in these domains might be enhanced by automation and big data analytics. Also, some of these new features, like e-credit scoring and mobile banking, provide a great deal of financial stability in the banking and finance sector. It is in these technical advances that Vietnam stands a chance to meet the aspirations to become an economy capable of engaging in high-tech and digital processes that responds adequately to the diverse needs of citizens within various geographical locations.

Vietnam's policies and regulations supporting digital transformation

That dedication to digital transformation in Vietnam is becoming an increasingly vital part of the nation's socioeconomic growth. The Vietnamese government has proactively implemented a series of policies, regulatory frameworks, and strategic action plans for it recognizes how impactful digital technologies could be. These measures are intended to promote innovation, reinforce digital infrastructure, and develop an

environment supportive of the growth of the digital economy. In line with the larger socio-economic goals of the nation and strengthening its competitive advantage in the global market, such initiatives show clear vision to build Vietnam into a global lead in digital transformation by 2030 (Table 3).

Table 3 – Key policies and programs for digital transformation in Vietnam

Policy/Regulation	Year	Main Aim
Resolution No. 52-NQ/TW on a number of policies and strategies to proactively participate in the Fourth Industrial Revolution	2019	The objective is to create a strong environment for regional advancement and keep Vietnam in the top three ASEAN nations on the Global Innovation Index (GII). By 2030, more than 30% of GDP will come from the digital economy
National Digital Transformation Program to 2025, vision to 2030	2020	Increase digital economy contribution to 20% of GDP by 2025; rank among top 50 in e-Government
Program to support small and medium enterprises in digital transformation	2021	Support digital adoption in SMEs through subsidies and tax incentives
National Strategy on Green Growth for the 2021-2030 period, with a vision to 2050	2021	Defining that through cutting-edge technology, digital transformation, contemporary governance, and the construction of sustainable infrastructure, green growth propels economic change
Program to Support Digital Transformation of Enterprises in the 2021-2025 Period	2021	By 2025, the program expects 100% of enterprises to be more conscious of digital transformation. Support will be provided to at least 100,000 organizations, including training, consultation, self-assessment tools, and links to digital transformation solutions
Circular No. 06/2022/TT-BKHĐT of the Ministry of Planning and Investment	2022	Regulations offer SMEs technical and advisory assistance, including financial assistance for the purchase or rental of authorized digital transformation solutions. In order to suggest suitable assistance measures, SMEs evaluate their preparedness for digital transformation

Source: Authors

Small and medium-sized enterprises are the building blocks of the Vietnamese economy, while over 98% of the total number of businesses account for this part[9]. These enterprises provide a substantial contribution toward national production and employment, both being a coveted basis for economic stability. Thirteen thousand and eight hundred companies across sixty-three provinces and cities in Vietnam were trained in digital transformation by the end of 2024. Additionally, almost four hundred enterprises were included in developing and implementing fully operational digital transformation roadmaps, and twenty-eight enterprises received tailored on-site training[10]. This variation in business approach and operational scope is indicative of how dynamic the market is and how adaptable businesses are, more so in relation to rapid globalization.

Vietnam's vision for digital transformation goes beyond economic interest to juggle the need for social advancement and sustainable development. Establishing the country as a technological innovation and deployment leader regionally is one of the central goals. Vietnam's attempt to tap the potential of the Fourth Industrial Revolution involves transforming its economy, enhancing governance, and uplifting citizens' well-being. In other words, it involves ensuring the integration of the nation into the global digital economy,

[9] *White Book on Women-Owned Small and Medium Enterprises Released. Source: https://dangcongsan.vn/kinh-te/cong-bo-sach-trang-ve-doanh-nghiep-nho-va-vua-do-phu-nu-lam-chu-658405.html (accessed on 17.03.2025)*

[10] *Policy to support businesses in digital transformation and innovation. Source: https://dangcongsan.vn/kinh-te/cong-bo-sach-trang-ve-doanh-nghiep-nho-va-vua-do-phu-nu-lam-chu-658405.html (accessed on 11.03.2025)*

improving productivity, and enhancing competitiveness.

Key to this idea is the objective of contributing GDP to the digital economy. This means leveraging digital tools and platforms to help foster innovation in the core sectors of manufacturing, agriculture, and services. The internet infrastructure extension projects aim to ensure connectivity across the country, thus providing equal access to digital services and eliminating the digital divide between urban and rural contexts. The policy messages stimulate growth based on the belief the benefits of the digital turn will flow through to all walks of life.

Another key aim is to build a competitive digital ecosystem that gives people and enterprises the tools and resources they need to be competitive in the digital age. Labor upskilling, business support, and technology development are encouraged by the government in order to facilitate innovation and productivity. Data governance and Cybersecurity are equally essential and are highly prioritized to build trust and resilience in the digital economy. Vietnam also aims to plug regulatory gaps and promote responsible behavior online to create a safe, welcoming space for domestic and international investment in the digital sector. Together, this set of initiatives aims to ensure that Vietnam's digital transition provides for growth that is fair, sustainable, and innovative.

Challenges for Vietnam in the Digital Transformation

Vietnam has achieved phenomenal successes in digital transformation, but many obstacles still stand against its longer-term goals. Some of the major challenges include cybersecurity deficiencies, workforce readiness, obsolete or incoherent regulatory frameworks, and limitations in digital infrastructure. These obstacles must be overcome if Vietnam's digital transformation initiatives are to be inclusive, successful, and sustainable. Overcoming these barriers will require cross-sectoral collaboration, giving resilience, creativity, and equitable access to digital resources primacy.

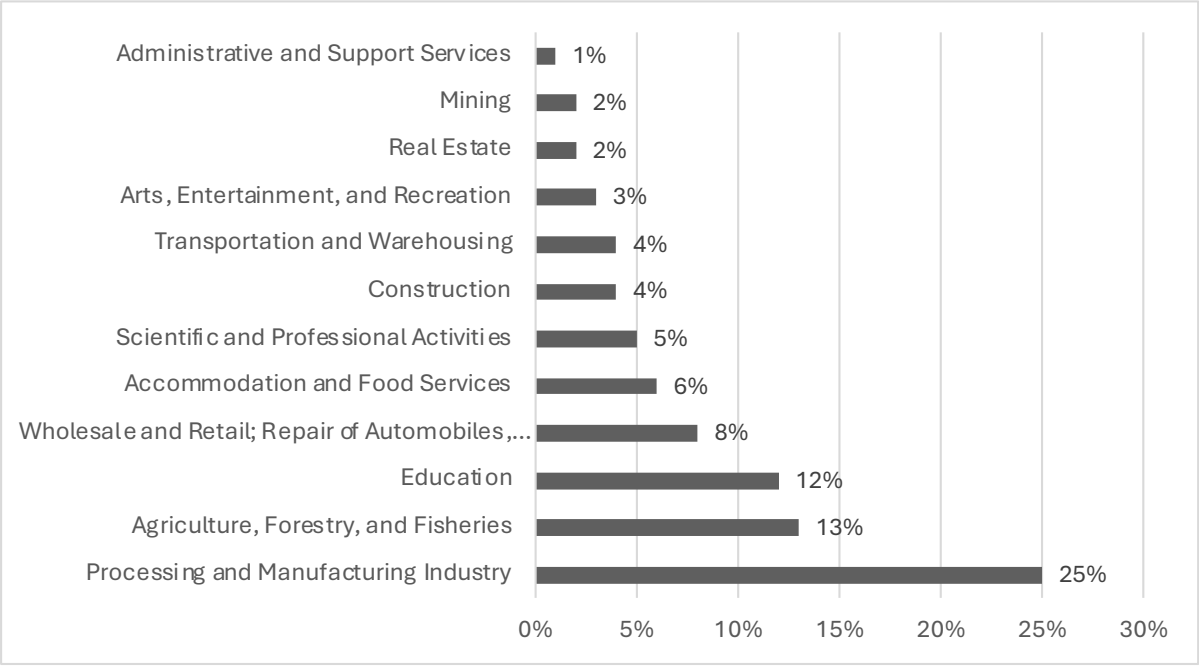

Figure 2. Sectoral Distribution of Digital Transformation Readiness Among Enterprises in Vietnam, 2023
Source: Annual report on digital transformation of Vietnamese enterprises, 2023[11]

Vietnam's businesses encounter a wide range of obstacles in their digital transformation, which reflects different levels of preparedness and ability to adopt new technologies (Figure 2). While some businesses are aggressively using digital solutions to boost productivity and competitiveness, others face major challenges including labor preparedness, insufficient infrastructure, and few resources. These difficulties highlight the

[11] *Annual report on digital transformation of Vietnamese enterprises, 2023. Source: https://digital.business.gov.vn/wp-content/uploads/2024/04/Annual-Enterprise-DX-report_final_EN.pdf (accessed on 15.03.2025)*

necessity of sector-specific approaches and encouraging laws in order to close the digital divide, encourage creativity, and guarantee a fair and long-lasting economic transition.

There are significant variations in understanding and resource distribution across industries areas in Vietnam's digital transformation environment. The strategic importance and revolutionary potential of digital technologies are still not completely implemented by many organizations, communities, and businesses. For small and medium-sized businesses (SMEs) in Vietnam, this problem is especially severe (Figure 3).

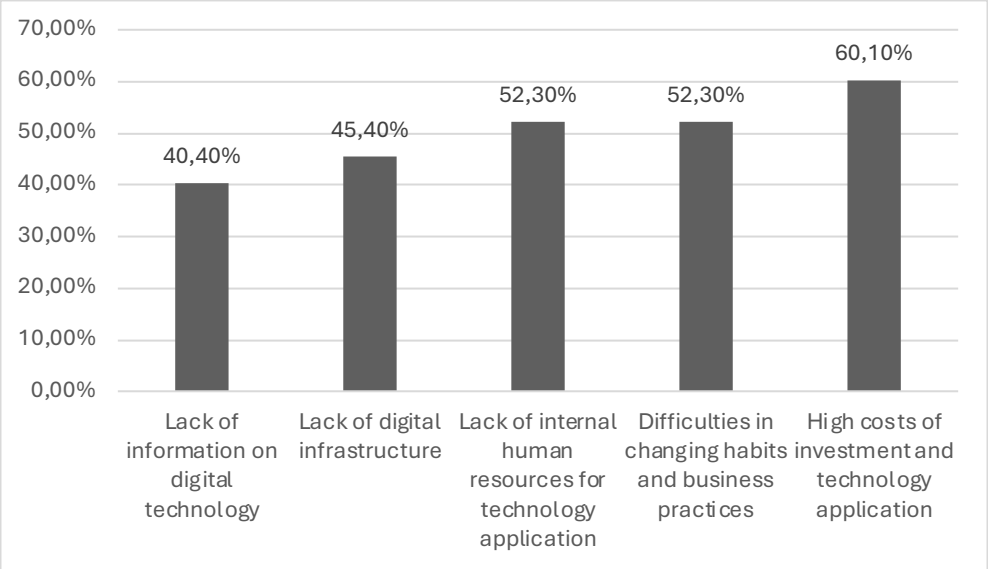

Figure 3. Top 5 barriers that Vietnamese businesses encounter in the process of digital transformation
Source: Barriers and difficulties of businesses when transforming digitally[12]

Moreover, while the community's overall digital literacy has improved, there still are very clear gaps – particularly in remote, border and island areas, as well as areas populated by ethnic minorities[13]. In these places, the more obvious presence of unequal access is compounded by a lack of digital skills and knowledge that leads to less engagement with technology, making the digital gap wider still. More must be done to tackle these discrepancies, through better public-private partnerships, targeted infrastructure investment, and a lot more widespread digital education initiatives to ensure all, equitable and sustainable digital transformation across the country.

Vietnam's quick embrace of digital technologies has made it more vulnerable to various cybersecurity risks. In 2021, Vietnam was one of the top 10 countries most affected by cyberattacks, indicating how vulnerable its digital infrastructure is[14]. The absence of strong cybersecurity frameworks and poor cybersecurity knowledge among individuals and businesses all contribute to this risk. Many businesses lack thorough security procedures, making sensitive information and vital systems vulnerable to hacking, financial fraud, and other crimes. These cybersecurity issues pose a serious obstacle to sustained prosperity as Vietnam continues its digital transition, necessitating immediate government and private sector cooperation to create a robust digital ecosystem.

Digital transformation entails the automation of repetitive tasks and the replacement of traditional jobs. In Vietnam, this could result in sweeping changes in labor markets which could, especially in industry and agriculture, threaten jobs for a significant share of the work force. Estimates suggest that, by 2030, as many as 1.3 million jobs in these sectors could face risk from automation, giving cause for concern about

[12] *Barriers and difficulties of businesses when transforming digitally. Source: https://digital.business.gov.vn/2153-2/ (accessed on 19.03.2025)*
[13] *Identifying challenges in digital transformation. Source: https://www.mof.gov.vn/webcenter/portal/thtk/pages_r/l/chi-tiet-tin-tin-hoc-va-thong-ke?dDocName=MOFUCM270788 (accessed on 08.12.2024)*
[14] *Which Countries are Most Dangerous? Cyber Attack Origin – by Country. Source: https://www.cyberproof.com/blog/which-countries-are-most-dangerous/ (accessed on 08.12.2024)*

rising unemployment and social inequality[15]. High-level digital jobs provide new opportunities but typically demand advanced skills that are often lacking in a large section of the low-skilled labor force, giving rise to an ever-widening skills' gap. Unless the government and other stakeholders embark on strong reskilling programs and planned interventions, the change will endanger the disadvantaged sectors, create a disruption against inclusive economic growth, and further deepen socio-economic fissures.

Another challenge Vietnam faces on its road to digital transformation is that of brain drain, losing some of its best-trained and most employable citizens to greener pastures abroad due to a scarcity of local opportunities or better incentives elsewhere. As the international demand for IT skills grows, keeping Vietnam's top digital talent should be of utmost priority. This will include competitive salaries, improvements in the working conditions, and an increase in domestic career opportunities. The government could further create a more nurturing environment for innovation by backstopping tech firms, research projects, and industry-academia partnerships. It might even be possible to reverse the trend by enticing foreign experts back to Vietnam through tax rebates or the possibility of investment in tech ventures.

These are the challenges that the digital transition now presents for Vietnam. While the government has started to make some headway regarding these concerns, the outcome of discussion of these pressing points will ultimately depend on whether there's collaboration between the private sector and the public. For digital transformation to deliver equal and sustainable benefits in Vietnam, improvements must be made in infrastructure deficit, skills enlargement, proper rating of the existing legal and regulatory environment, and stimulation of resilience against cyber threats. These challenges could be met in a manner that accomplishes its ambitious aspirations and sets an example in the world's thinking about the development course that has similar issues.

Policy Recommendations for Advancing Vietnam's Digital Transformation

A robust, universal, and concerted digital infrastructure is crucial for Vietnam's digital transformation. Though connectivity is increasing, inequalities still lead to differences in harmonic connectivity levels among populations, with significant differences in remote and rural populations. The government should promote public/private partnerships in order to build momentum for population expectations regarding both investments in a 5G network and the investment into high-speed broadband service measuring bandwidth and latency that provides some minimal service standard. Yet, the infrastructure required to reach unserved populations needs to be built by private telecommunications firms, who benefit from financial, investment, and tax incentives, to provide similar and adequate populations access to telecommunication services. Vietnam's second priority should be to ensure proper response to the supply of cloud services and protect data sovereignty where necessary, while at the same time allowing business the means to use digital technology; meaning that needed local data centers for business and industry need to be built in order to make this work.

As Vietnam moves toward a digital economy, it is vital to develop a skilled workforce in digital values. Digital literacy formation cannot work in isolation, this being included at all levels of our national education system is thus a prime requirement. Universities should partner with tech corporations in private industry to provide programs relevant to employment in the field, such as cybersecurity, data science, and artificial intelligence training. After that, on-the-job skills upgrading and technical transition by the national upskilling-reskilling should minimize the risk of redundancy for workers across a wide range of occupations, including those most directly in line with the digital economy. Awareness campaigns within underprivileged and rural communities become paramount in instilling knowledge that leads to a fair share in inputs to the digital economy.

There is an imperative of developing such an ecosystem that, in the digital world, would be safe and reliable for the development of Vietnam in the digital age. A comprehensive national cybersecurity policy should be developed by the government, which would address various vulnerabilities in the system and provide protection for its vital national infrastructure. This policy will include the establishment of Regional Training Centers and fund the training of committed specialists in combating cybercrimes, thereby increasing

[15] *OOOLAB highlights urgent need for upskilling. Source: https://vir.com.vn/ooolab-highlights-urgent-need-for-upskilling-109805.html (accessed on 05.12.2024)*

resilience against them. Public awareness campaigns: people and organizations, including children, should be educated about the threats of the internet and acceptable conduct on digital platforms and often seminars on safety practices; besides, building confidence in the digital sphere.

In the same light, it is vital to ensure that Vietnam's digital transition is inclusive. The government should provide funding for affordable digital devices and internet access for low-income families. Targeted activities such as mentorship and training programs for disadvantaged groups, primarily women and ethnic minorities, may engage them further in the digital economy. Extension of e-governance platforms in rural areas would enable people in the digital age to access basic services such as health and education.

Through these defined approaches, Vietnam can therefore take full advantage of the opportunities consequential to the digital transformation and not escape the consequences. Injecting infrastructure, investing in digital skills, updating its regulatory frameworks, and promoting inclusive prosperity will place Vietnam at the forefront of any developing country in the digital era. The government, companies, and civil society must jointly contribute to fulfilling the vision and ensuring that digital transformation will spur equitable and sustainable growth for all.

Conclusion

This is a manifestation of the interplay of possibilities, hurdles, and opportunities concerning the modernization of the country's economy through digital transformation. Vietnam has become a digital trailblazer in Southeast Asia thanks to the country's advantageous demographic situation, a strong business environment, and a proactive regulatory framework, which have helped Vietnam blossom. Rapidly growing ecommerce and a significant GDP contribution from the ICT industry testify to Vietnam's readiness to transition into the digital economy. All these achievements, buttressed by concerted efforts in infrastructure and research, place Vietnam as an emerging nexus of wealth and growth driven by technology.

However, different challenges are related to the disruption that digitalization can create. The persistent divides represent the disparities among various societal groups in terms of opportunity and access to the new relevant technologies. Security vulnerabilities expose businesses and organizations to data breaches and cyberattacks that bring tremendous financial loss. Also, the closure of traditional businesses, along with the widening skills gap, is likely to aggravate differences among the working class and even threaten progress. These challenges indicate a need for targeted efforts to ensure as many members of society reap benefits from the digital revolution.

In dealing with these problems and maintaining development, Vietnam is required to put more commitment into its digital transformation. Top of the agenda will be investment in new technologies such as artificial intelligence and big data, alongside the construction of solid and high-speed internet infrastructure. Bridging the skills gap and propelling digital literacy, especially in disenfranchised groups, will be key in ensuring broad participation in the digital economy. Building further on this, policies that promote public-private partnerships can combine resources and ideas to address problems more effectively.

There are many lessons Vietnam can indicate to those other developing countries engaged in their own digital transformation. The focus on innovation management, proactive rule, and incorporation of sustainable goals into the digital projects illustrates how indispensable flexibility and inclusivity are in this digital age. This frame of thinking augurs the need to strike a balance pertinent to the digital transformation-namely, ensuring that it is a strong enabler of holistic and equitable growth-driven by technical innovation and social equity plus welfare commitment.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR'S CONTRIBUTIONS

Dinh Le Hong Giang – conceptualization; supervision.
Nguyen Huu Phu – writing – original draft.

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The role of the startup ecosystem in shaping the innovative competitiveness of a national economy (case studies of Sweden and Estonia)

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ORIGINAL ARTICLE

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Abstract. This article examines the role of startup ecosystems in shaping the innovative competitiveness of a national economy, using Sweden and Estonia as case studies. The analysis focuses on the key elements of successful ecosystems, including the institutional environment, access to finance, human capital development, and the level of digitalization. Particular attention is paid to a comparative analysis of two distinct models: the Swedish model, characterized by a complex, multi-layered architecture integrating the state, universities, and large corporations, and the Estonian model, which is oriented towards the digitalization of administrative infrastructure and the creation of an open global ecosystem. The positive effects of developing startup ecosystems are considered, such as inbound investment flows, an increase in the number of high-tech companies, and improved national standings in global competitiveness rankings. The relevance of the topic is driven by the growing importance of innovation as a key factor for economic growth and resilience in the context of global competition. The aim of this research is to identify the relationship between the development of startup ecosystems and the level of national competitiveness, as well as to determine key trends, barriers, and prospects for countries with emerging innovation ecosystems. The research logic is as follows: first, the conceptual framework and theoretical foundations of innovative competitiveness and startup ecosystems are outlined; subsequently, a detailed comparative analysis of the Swedish and Estonian models is conducted, employing statistical data and correlation analysis to identify key success factors. The study is based on comparative, statistical, and analytical methods, as well as on the analysis of contemporary scientific publications and reports from international organizations. Based on the analysis, it is concluded that the competitiveness of a national innovation economy is determined by the efficacy of administrative institutions and the degree of digitalization. The findings of this research can be utilized for developing small and medium-sized enterprise (SME) growth strategies in other countries.

Keywords: startup ecosystem; national competitiveness; innovative competitiveness; national innovation system; comparative analysis

JEL codes: O31, O32, G23, L26, O38, O52

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Introduction

The concept of national competitiveness in the contemporary context has become a cornerstone of policies aimed at strengthening a state's economic resilience and innovative capacity on the international

stage. Widely applied in economics, marketing, business, international relations, politics, and education, the concept of competitiveness serves as a tool for a comprehensive assessment of an economic entity's development, as well as for identifying its strengths and weaknesses [14].

The new wave of innovative company creation – startups – emerged at the turn of the millennium [6] and has since become an integral part of the modern economic landscape. Startups, as components of an ecosystem and a business model element, are established under conditions of extreme uncertainty within environments where innovation is the focal point of operational activity [3]. A country's ability to foster favorable conditions for entrepreneurship and startup ecosystems determines its level of long-term prosperity.

The European Union's enlargement process has intensified economic heterogeneity within the region, revealing disparities in innovative potential between older and newer member states, which is reflected in the dynamics of their entrepreneurial activity and competitive capabilities [12, 15]. The European startup market is growing and becoming increasingly attractive to foreign acquirers, particularly from the United States [13]. Regional studies have indicated that macroeconomic stability and skills, namely human capital, are the most critical factors influencing the creation and scaling of startups and technology companies in Europe, while the size of the national market remains the least significant aspect [9]. It has been established that more developed European Union countries provide startups with an institutional competitive advantage, whereas the gap in success factors between highly developed and catching-up economies can be attributed to human capital and institutional frameworks [19].

The foundation for enhancing a state's competitiveness lies in the innovative activity of enterprises, which shapes the development trajectory of the national economy. Globalization, in turn, has increased pressure on the small and medium-sized enterprise (SME) sector, incentivizing organizations to optimize their production processes. Startups play a particularly crucial role by creating new technological solutions, driving digital transformation, and ensuring a continuous influx of innovation across various industries. Their operational prospects are determined by the quality of institutional and infrastructural conditions – such as access to financing, state support for innovation, and regulatory transparency – which become fundamental success factors. The business environment constitutes a multi-level system encompassing economic, political, and technological factors, as well as parameters of the market's competitive structure [5].

This research analyzes the correlation between the development of startup ecosystems in Sweden and Estonia and their respective levels of national competitiveness. It aims to identify key trends, barriers, and prospects for the development of innovative entrepreneurship as a driving force behind the competitive advantages of European nations.

Main Part

According to contemporary scholarly understanding, the concept of innovative competitiveness is a property of a national economy that entails the creation, adoption, and scaling of new solutions, enabling it to maintain a sustainable advantage in the long term [1]. A state achieves stable long-term development when it possesses a large number of innovative small and medium-sized enterprises (SMEs). It is these companies that render an economy flexible and allow it to adapt swiftly to changes. Moreover, the increasing number of developing startup ecosystems correlates with the growing innovative activity of nations worldwide over recent decades [4].

Modern academic literature features several conceptions of the "startup ecosystem." Evolving from the definition of a "business ecosystem" – an environment that accumulates opportunities for launching ventures aimed at creating technological products [11] – a startup ecosystem is "a dynamic and self-evolving organism, constituting a set of interconnected actors, institutions, processes, and resources that collectively shape favourable conditions for the emergence, development, and scaling of innovative companies" [21].

The development of innovation ecosystems addresses a range of key issues in a comprehensive manner, acting as a catalyst for positive change. Within the context of the environmental agenda, such ecosystems serve as testing grounds for the creation and implementation of 'green' technologies, whether it involves developing more efficient solutions in renewable energy, adopting circular economy principles for waste

recycling, or creating smart systems utilizing AI and IoT to optimize energy consumption and reduce carbon footprints [17]. Concurrently, they transform the landscape of trade relations by generating entirely new markets for high-tech goods and services, thereby enhancing the competitiveness of national companies on the global stage and fostering the growth of digital trade through the adoption of blockchain and fintech [18]. Furthermore, their impact extends beyond these areas, positively affecting the social and urban environment – through improved quality of life resulting from breakthroughs in medicine and education, as well as by attracting top international talent to a region, which creates a self-reinforcing environment for knowledge generation and sustainable competitive advantage in the long run.

As an integral component of the entrepreneurial ecosystem [2], the startup ecosystem constitutes a complex of digital and spatial resources that enable entrepreneurs to establish and scale high-technology businesses [12].

The complex network of interactions among participants is a noted characteristic, where constant horizontal and vertical linkages are formed. These connections stimulate knowledge circulation and accelerate the diffusion of innovations both within new ventures and established companies [16]. Thus, human capital, cultivated in a society where a significant proportion of the population holds higher education degrees and has opportunities for continuous learning and knowledge exchange, constitutes one of the fundamental elements for the development of a startup ecosystem.

It is crucial to highlight the necessity for diverse funding sources within the ecosystem. These sources enable startups to secure necessary capital at every stage – from ideation to mass market entry – thereby strengthening their path to profitability. This also depends on the level of development of the state's institutional and regulatory environment, including intellectual property protection mechanisms, and influences the growth rate of the startup ecosystem as an effective vector for developing the national business environment. This, in turn, ensures growth in the country's Gross Domestic Product and employment [5].

Digital startup ecosystems contribute to the diversification of a country's economic structure. It is important to note the growing prominence of the financial sector within the global startup ecosystem map. New generations of companies entering this market foster job creation and instigate a profound transformation of national and transnational markets through the development of fundamentally new financial products and services. Despite the initial negative impact of the COVID-19 pandemic on digital startups, it is noteworthy that the number of these companies grew 2.3 times faster than other small and medium-sized enterprises since 2019. A dominant component is the share of financial startups among unicorn companies (39.2%) – startups with a total valuation exceeding $1 billion[1].

The ecosystem's influence on the dynamics of venture and foreign investments presents a distinct area of scientific and practical interest. As research indicates [20], stable state support is a key factor in transforming a startup ecosystem into a hub for international capital. In the competitive struggle for global investments, those states gain an advantage that integrate the startup creation process with government support programs and strategic cooperation with large corporations. Beyond increasing the resource base of the national economy, the inflow of investments facilitates the diffusion of best practices, innovative management approaches, and modern technological standards.

The experience of European countries confirms that they serve as drivers of innovative development, providing economies with the flexibility to counteract the challenges of globalization[2]. As of 2024, 8 European states are ranked among the top 15 leaders in the global ranking: Sweden, Germany, France, the Netherlands, Switzerland, Estonia, Finland, and Spain (Figure 1).

In contrast to the business strategies of large European states, which focus on scaling within their domestic markets, the innovative potential of Sweden – a sparsely populated country with approximately 10 million inhabitants – serves as a driver for the global startup ecosystem. According to the 2024 Global Startup Ecosystem Index report (Startup Blink)[3], Sweden has maintained its position as the leading startup

[1] *A global startup research platform StartupBlink. Source: https://www.startupblink.com/?leaderboards (accessed on 17.07.2025)*
[2] *According to the Global Startup Ecosystem Index, compiled by the research center SturtupBlink. Global Startup Ecosystem Index 2024. Source: https://lp.startupblink.com/guanajuato-report/ (accessed on 17.07.2025)*
[3] *Global Startup Ecosystem Report 2024. Source: https://lp.startupblink.com/guanajuato-report (accessed on 17.07.2025)*

ecosystem within the European Union (Figure 1). A 33% increase in the number of financial companies between 2019 and 2024 indicates the growing competitiveness of the Swedish digital finance sector and rising investor interest in financial technologies.

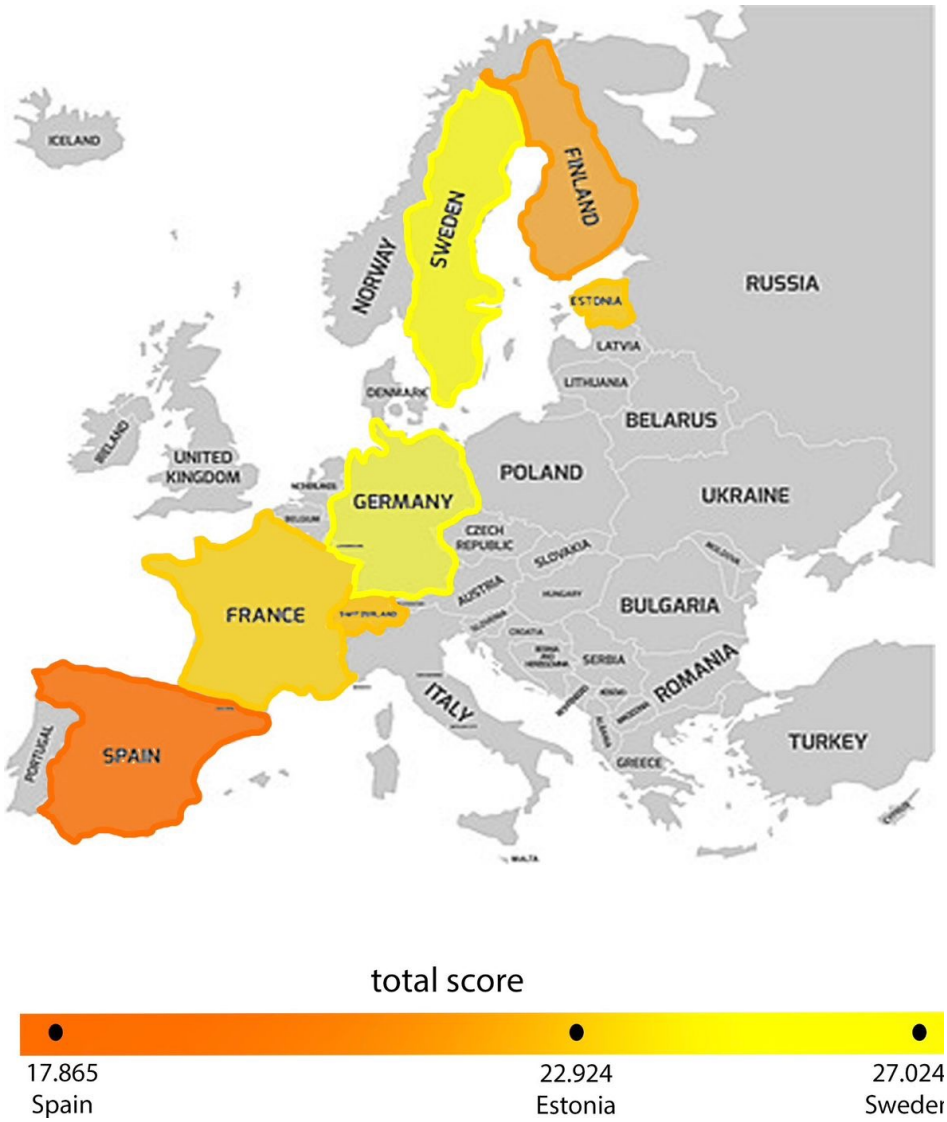

Figure 1. Distribution of European Countries Ranked in the Top 15 of the Global Startup Ecosystem Index in 2024

Source: Global Startup Ecosystem Index, 2024

Despite a high cost of living that can constrain startups lacking initial funding, Sweden ranks third in Europe by volume of venture capital attracted in 2024. Venture investments in the fintech sector have shown a consistently positive trend, peaking in 2021-2022 (exceeding €2 billion annually) and remaining at a high level throughout the period under review. Leading fintech companies – such as Klarna, iZettle, Trustly, and Tink – demonstrate a high degree of integration with the banking sector and global financial markets, reinforcing Sweden's position as a hub of European technological leadership. Lending to small businesses grew from €20 billion to €42 billion, confirming the existence of effective mechanisms for channelling capital into the innovation sector and a high level of trust in startups from financial institutions.

Between 2018 and 2024, the number of small enterprises (with up to 10 employees) increased by 78.7%, reflecting a high level of entrepreneurial activity and the efficacy of national business support institutions. This growth is attributable to the combined effect of macroeconomic factors and targeted state policy – specifically, programs offering credit, educational, and accelerator support for innovative entrepreneurship.

Notable initiatives include the independent Sweden Startup Nation effort[4], aimed at strengthening policies for startup support and business scaling. Furthermore, a residency program for self-employed immigrants allows entrepreneurs access to free higher education, thereby enhancing the country's human capital. This is corroborated by a positive correlation between the economically active population and the share of GDP expenditure on R&D (Figure 2).

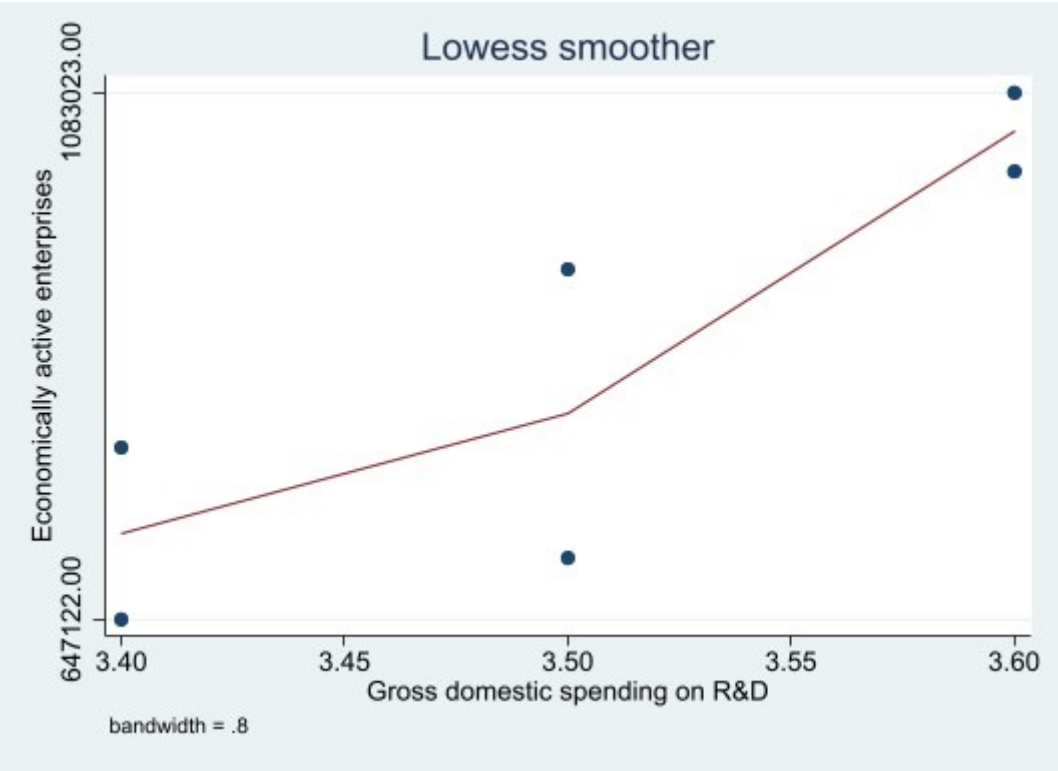

Figure 2. Locally Weighted Scatterplot Smoothing (LOWESS) for Economically Active Population vs. Gross Domestic Expenditure on R&D (GERD) as a Percentage of GDP in Sweden (2019–2024)
Source: Eurostat

Table 1 – Correlation Matrix of Key Indicators Underpinning the Development Dynamics and Investment Attractiveness of Startup Ecosystems in Sweden (2018-2024)

Key Indicators	Gross domestic spending on R&D, % of GDP	Population above 15 with higher education, %	Venture and growth capital. mil EUR	Economically active enterprises. Number (less than 10 employers)	New business lending, mln EUR	Volume of FinTech Investment, € million	Number of FinTech Companies
Gross domestic spending on R&D, % of GDP	1						
Population above 15 with higher education, %	0.7270	1					
Venture and growth capital, mln EUR	0.2026	0.8027	1				

[4] *Sweden Startup Nation (SSN). Source: https://www.swedenstartupnation.se/en (accessed on 17.07.2025)*

Key Indicators	Gross domestic spending on R&D, % of GDP	Population above 15 with higher education, %	Venture and growth capital. mil EUR	Economically active enterprises. Number (less than 10 employers)	New business lending, mln EUR	Volume of FinTech Investment, € million	Number of FinTech Companies
Economically active enterprises, number (less than 10 employers)	0.8377	0.7954	0.4107	1			
New business lending, mln EUR	0.4643	0.1720	0.72	0.3937	1		
Volume of FinTech Investment, € million	0.48	0.413	0.51	0.477	0.76	1	
Number of FinTech Companies	0.53	0.6	0.75	0.552	0.68	0.87	1

Source: Eurostat

A positive correlation (r = 0.72) was identified between the volumes of venture capital investment and bank lending, reflecting a multi-channel financing model that includes foreign direct investment and public support instruments. The correlation between the number of FinTech companies and the volume of bank lending (r = 0.68) confirms the significance of credit resource availability for the expansion of entrepreneurial activity. The strongest relationship is observed between venture investments and the number of FinTech companies (r = 0.75), indicating the sector's high sensitivity to the volume of capital raised.

The Swedish model of an innovation ecosystem is based on a complex institutional infrastructure that includes government agencies, universities, large corporations, acceleration platforms, and banks. This structure ensures the consolidation of resources and the formation of a sustainable innovation support mechanism, establishing Stockholm as the central Swedish startup hub for the FinTech sector. Its success is further bolstered by the Invest Stockholm program[5], which stimulates the growth of small and medium-sized businesses by fostering credit systems.

Despite a small domestic market, a population of less than 2 million, and a limited resource base, Estonia has accelerated its pace of new business development. Since 2020, the country has been the startup leader in Eastern Europe, and its lead over Lithuania, which holds second place in the region, has quadrupled. It is noteworthy that, according to the provisions of the Estonia White Paper 2021-2027[6], one of the country's strategic goals is to increase the innovation sector's contribution to 15% of GDP.

Data from 2019–2024 show that the number of FinTech companies in Estonia grew by approximately 35%, significantly exceeding the European average. Although this growth is lower in absolute terms than Sweden's, such high rates indicate a significant density of innovative activity per capita. This characteristic is typical of dynamically developing ecosystems and serves as a powerful factor in attracting international investment, as well as foreign experts and entrepreneurs.

The success of Estonian FinTech is largely the result of a unique institutional environment and a targeted state policy of digitalization. Key initiatives such as e-Estonia and the e-Residency program have played a pivotal role. They allow non-residents to establish businesses in Estonia quickly and remotely, which directly contributes to the globalization of the local ecosystem. Estonia is a global leader in implementing

[5] *Invest Stockholm Programme Outlook. Source: https://www.stockholmbusinessregion.com/ (accessed on 17.07.2025)*

[6] *This work has been completed as a result of the work of the Estonian State. Commission on Examination of the Policies of Repression. Source: https://www.riigikogu.ee/wpcms/wp-content/uploads/2015/02/TheWhiteBook.pdf (accessed on 17.07.2025)*

e-government services, the success of which is explained by the extensive use of blockchain technologies [16], which are actively developed within FinTech startups.

The digitalization of key administrative procedures – from business registration to tax reporting – has minimized transaction costs for startups and created attractive conditions for foreign entrepreneurs. This explains the positive correlation between the economically active population and the share of R&D expenditure in the country's GDP (Figure 3).

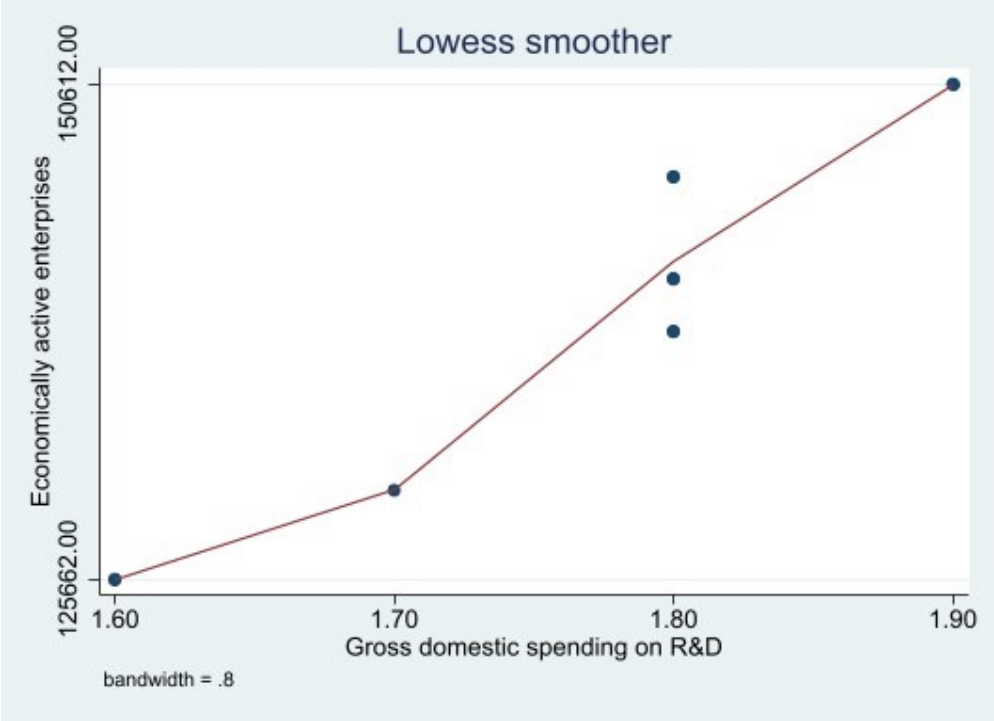

Figure 3. Locally Weighted Scatterplot Smoothing (LOWESS) of the Relationship Between Economically Active Population and Gross Domestic Expenditure on R&D (GERD) as a Percentage of GDP in Estonia (2019-2024)

Source: Eurostat

Over the period from 2019 to 2024, the volume of venture capital investment in FinTech increased from €45 million to €150 million, indicating growing investor confidence in the maturity of the innovation ecosystem. In parallel, small business lending volume rose from €1.2 billion to €2.1 billion, reflecting improved access to financial resources and heightened confidence from banks and institutional investors in the innovation sector. The synchronous growth of both indicators underscores a comprehensive strengthening of financial support for startups. This is corroborated by a strong positive correlation (r = 0.95) between the volume of investment and lending to new businesses.

Table 2 – Correlation Matrix of Key Indicators Underpinning the Development Dynamics and Investment Attractiveness of the Startup Ecosystem in Estonia (2018-2024)

Key Indicators	Gross domestic spending on R&D, % of GDP	Population above 15 with higher education, %	Venture and growth capital. mil EUR	Economically active enterprises. Number (less than 10 employers)	New business lending, mln EUR	Volume of FinTech Investment, € million	Number of FinTech Companies
Gross domestic spending on R&D, % of GDP	1						

Key Indicators	Gross domestic spending on R&D, % of GDP	Population above 15 with higher education, %	Venture and growth capital. mil EUR	Economically active enterprises. Number (less than 10 employers)	New business lending, mln EUR	Volume of FinTech Investment, € million	Number of FinTech Companies
Population above 15 with higher education, %	0.93	1					
Venture and growth capital, mln EUR	0.3	0.25	1				
Economically active enterprises, number (less than 10 employers)	0.95	0.87	0.15	1			
New business lending, mln EUR	0.29	0.26	0.95	0.22	1		
Volume of FinTech Investment, € million	0.69	0.369	0.733	0.284	0.56	1	
Number of FinTech Companies	0.748	0.5	0.64	0.821	0.532	0.42	1

Source: Eurostat

A positive correlation was identified between the volume of investments and bank lending (r = 0.56), confirming the systemic nature of the ecosystem's development, where private and public capital form a stable financial foundation for innovation. A significant proportion of new small enterprises are oriented towards international digital markets and high-tech services [7]. This strategy is driven by two key factors: Estonia's active participation in international startup support programs and the targeted development of human capital. For instance, in 2024, the share of the population with higher education reached 37.8%, and the quality of specialist training meets leading European standards.

A positive correlation was also found between the number of FinTech companies and the volume of venture investments (r = 0.64), indicating a direct influence of investment activity on the sector's growth and the creation of new enterprises. Furthermore, Estonia is home to the headquarters of the global startup accelerator Startup Wise Guys, which has invested in over 400 startups worldwide.

The key distinctions between the two countries lie in the realm of absolute metrics: the scale of their national economies, the number of FinTech startups, and the volumes of attracted investment. For example, the total volume of venture investments in FinTech over six years in Sweden amounted to €9.5 billion, whereas in Estonia it was approximately €600 million. At first glance, this confirms Sweden's leadership in terms of aggregate innovative potential.

However, the picture changes when shifting to relative indicators. Considering the significant difference in population size (10.5 million in Sweden versus 1.3 million in Estonia), Estonia demonstrates comparable, and in some parameters, even superior dynamics. Metrics such as the density of innovative activity and the growth rate of FinTech companies per capita position it as a full-fledged and confident regulator of a startup ecosystem. Specifically, over the five-year period, the growth in the number of FinTech unicorns in Estonia

reached 35%, slightly outpacing the Swedish figure of 33% (Figure 4).

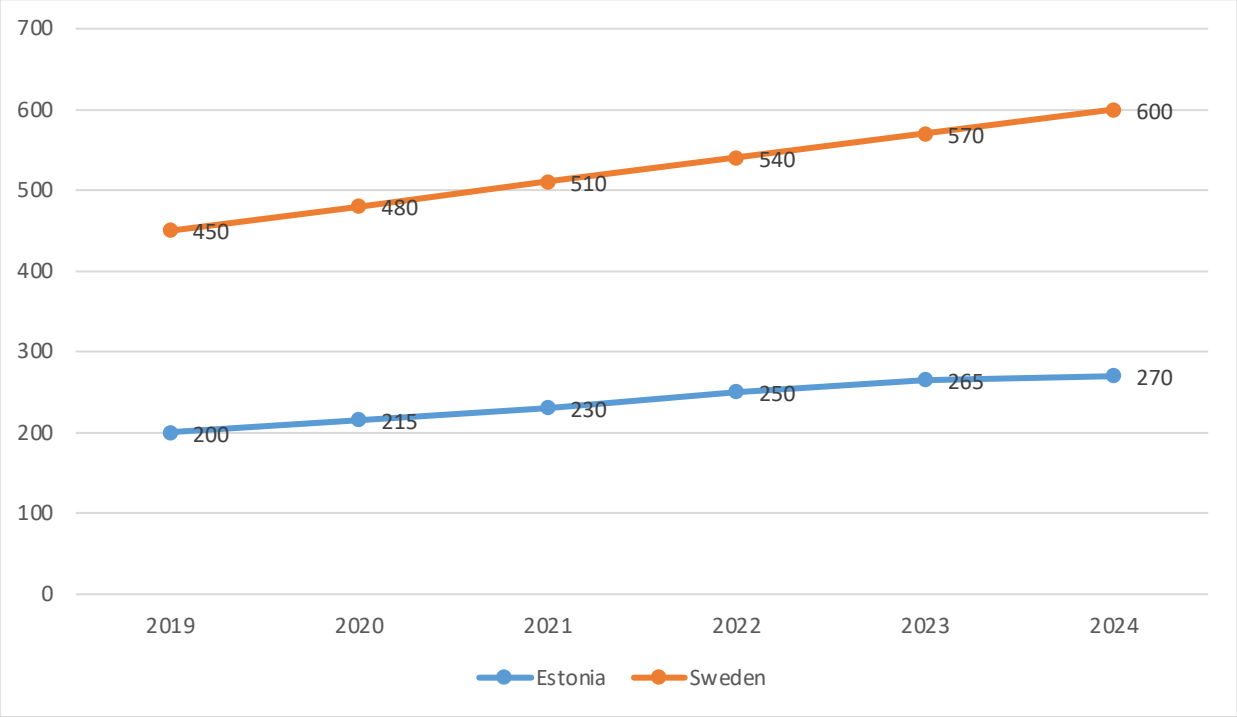

Figure 4. Number of FinTech Unicorn Companies Founded in Sweden and Estonia, 2018-2024
Source: Eurostat

The startup ecosystem exerts a substantial influence on a country's position in the Global Competitiveness Index (GCI)[7], calculated by the World Economic Forum. This index assesses nations' capacity to ensure sustainable economic growth, taking into account factors such as infrastructure, macroeconomic stability, health and education, labour market efficiency, innovation potential, and business dynamism.

In developed Northern European economies, particularly in Sweden, startups function to reinforce a pre-existing, robust innovation system. Their impact is reflected in the improvement of national scores within those GCI components related to innovation, capital market development, and human capital quality. According to the ranking[8], Sweden holds 8th place globally in 2024. This is explained by the active development of venture capital and university spin-offs (for instance, from KTH and Chalmers University of Technology), which increases private investment in R&D, thereby directly enhancing Sweden's standing in the "Innovation ecosystem" pillar [10].

In Estonia, which holds the 27th position in this ranking, startups, conversely, serve a compensatory function – acting as a tool for accelerated growth and institutional modernisation. They enhance flexibility, digital readiness, and the efficiency of public administration. The positive impact of social welfare expenditure is emphasised as a fundamental stimulus for economic growth and a facilitator of the state's innovative activity [8]. Companies such as Bolt, Veriff, Pipedrive, and Wise demonstrate how startups can influence macroeconomic parameters reflected in the competitiveness index: they boost the export of IT services, increase labour productivity, and stimulate inflows of foreign direct investment.

A 49% annual growth in the startup sector's turnover (according to Startup Estonia[9]) directly affects the metrics for "Market Size," "Business Dynamism," and "Innovation Capability," thereby strengthening the country's overall score. Consequently, fostering innovative activity promotes employment and income growth, enhances product quality and production efficiency, which collectively improve the population's standard of living. For developing economies, innovation strategies serve as a tool for accelerated economic convergence

[7] *GCI is a framework that assesses a country's economic competitiveness based on factors like institutions, policies, and productivity.*
[8] *Global Competitiveness Report 2024. Source: https://databank.worldbank.org/metadataglossary/africa-development-indicators/series/GCI.INDEX.XQ (accessed on 17.07.2025)*
[9] *Startup Estonia Report 2024. Source: https://startupestonia.ee/ (accessed on 17.07.2025).*

and sustainable development [10].

Conclusion

Thus, the Swedish and Estonian experiences in developing innovative potential within their startup ecosystems demonstrate that the competitiveness of a national innovation economy is determined by the efficacy of administrative institutions and the degree of digitalization within the entrepreneurial environment. Building sustainable leadership in the realm of innovative products requires comprehensive transformations, including the modernization of legal and tax frameworks, the development of the educational system, support for the startup ecosystem, and deeper global economic integration.

Significant differences are observed in the institutional approaches of the two countries. The Swedish model is characterized by a complex, multi-layered architecture that integrates government agencies, universities, corporations, powerful accelerators, and financial institutions. This coalition of key stakeholders enables the consolidation of substantial resources and the implementation of comprehensive national-scale programs to support innovative entrepreneurship.

An important consequence of this integration is the close linkage between FinTech companies (such as Klarna, iZettle, Trustly, Tink) and traditional banks, as well as their deep involvement in the global economic system. In contrast, the Estonian model is focused on the digitalization of administrative infrastructure, which attracts not only local but also international entrepreneurs, rendering the Estonian ecosystem open and flexible. This allows Estonian FinTech companies (like Wise, Monese, Pipedrive, Bolt) to pursue rapid scaling strategies, initially targeting international markets from their inception.

The findings of this research can be utilized by countries with emerging business ecosystems to formulate their own strategies for the development of small and medium-sized enterprises and to adapt successful foreign models to their specific national contexts.

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CONFLICT OF INTEREST

One of the authors of the article is the editor-in-chief of the journal.

AUTHORS' CONTRIBUTION

Svetlana N. Rastvortseva – conceptualization, project administration, writing – original draft.
Sofiia A. Panasiuk – investigation, writing – review & editing.
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The economics of sustainable finance: a comparative analysis of regulatory models for green financial instruments in the jurisdictions of EU, USA, China, and Russia

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ORIGINAL ARTICLE

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Abstract. Recent climate threats and carbon regulation provide the global transformations of the financial system. Therefore, the green bond market is becoming a key indicator of the transition to a post-carbon economy. Consequently, the growth of green financing and a concurrent crisis of trust determine the relevance of the research. Those occurred as a result of fragmented regulatory frameworks, inconsistent taxonomies, and practices of greenwashing. Moreover, they threaten the resilience of the financing ecosystem. The objective of the research is a comparative analysis of regulatory models in the EU, USA, and China, as well as a diagnosis of institutional challenges in Russia and other developing economies. The research purposes are as follows: (1) analysis of the regulatory base; (2) examining the relationships between regulatory stringency and the cost of capital; (3) assessment of verification and disclosure mechanisms; (4) development of an Integral Regulatory Maturity Rating (IRMR) model; (5) recommendations for the adaptation of international best practices. The methodology involves systems and comparative analysis, case studies, expert scaling, and unique coefficients. According to the research results, stringent regulation (EU) ensures transparency but reduces flexibility; market autonomy (USA) stimulates innovation but increases information asymmetry; and centralised incentivisation (China) mobilises resources but diminishes accountability. The following critical institutional deficits were identified for Russia: a low regulatory maturity index (IRMR = 0.48), a fragmented verification infrastructure with an independence coefficient of 0.31, weak integration with international standards (0.46), and insufficient fiscal incentives. The Russian green bond market requires a comprehensive modernisation of its regulatory structure, including harmonisation of the national taxonomy, the establishment of an independent verification system, and more active participation in global sustainable finance initiatives. The practical significance of the work is in proposed development strategy for the Russian green bond market. The scientific novelty consists in an experimental maturity model with non-linear weights and the identification of a paradox: high formal maturity increases transaction costs, forming an inverse relationship between legitimacy and affordability. This research contributes to institutional economics, the theory of information asymmetry, and the political economy of sustainable finance.

Keywords: green bonds; sustainable finance taxonomy; regulatory maturity; ESG verification; institutional dysfunction

JEL codes: G18, G28, Q58, O16, Q01, G32, D82

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Introduction

The global structure of financial markets is under a fundamental transformation due to the economic decarbonisation and the goal of achieving climate neutrality by mid-century. Emerged as a niche instrument in the 2000s, green bonds have become a systemically important element of sustainable finance. Moreover, they attract capital towards environmental projects [1, 2]. However, their exponential growth exacerbates institutional contradictions: heterogeneity in regulatory approaches, divergence of taxonomies, and greenwashing risks.

Contemporary literature on sustainable finance demonstrates growing interest in regulatory harmonisation and the effectiveness of green financial instruments. Recent research reveals key trends in this field. Gilchrist and Swanson analyse the impact of regulatory uncertainty on green bond price volatility. They also consider the increasing the risk premium by 15-20 basis points due to lack of unified standards [18]. McAllister et al. investigate the role of institutional investors in shaping ESG reporting standards. They also emphasise the critical importance of independent verification for maintaining market trust [19]. Wang and Zhang provide a comprehensive analysis of the evolution of China's green finance system, demonstrating the effectiveness of state incentives under clear taxonomic criteria [20]. Rodriguez-Moreno and Fernandez study the transmission mechanisms of regulatory changes to the cost of capital in the European context. They identify nonlinear effects of regulatory stringency [21]. Simpson and Cole focus on the problem of greenwashing and propose early detection indicators for misleading practices [22]. Leong et al. analyse development features of green bond markets in Southeast Asian countries, highligh the role of regional cooperation in standardisation [23]. Mueller and Schmidt investigate the impact of technological innovations on the effectiveness of monitoring green project compliance with stated criteria [24]. Patel et al. study the relationship between the development of national taxonomies and integration into global sustainable finance chains [25]. Anderson and Clark present a comparative analysis of how different regulatory models affect innovation activity in green technologies [26]. Finally, Yoshida, and Tanaka explore the development of the green bond market under economic instability and propose adaptive regulatory mechanisms [27].

Transparency is the foundation of investor trust. It ensures information symmetry between issuers and bondholders regarding the use of proceeds and the environmental impact of projects [3]. Third-party verification confirms compliance with the ICMA Green Bond Principles (GBP) or the Climate Bonds Standard (CBS) [3]. Sustainable finance taxonomies are classification systems for economic activities based on environmental criteria. They form the basis for identifying “green” projects and minimising reputational risks [5].

However, the pursuit of the harmonisation paradoxically forms the fragmentation: the stringent regulation of the EU contrasts with the market-based self-regulation of the United States; China's state-directed approach offers a third alternative [6]. Russia and other emerging economies balance between the integration into global sustainable finance chains with the preservation of national specificities.

Hence, the purpose of the research is a comparative analysis of regulatory models for green financial instruments in the EU, the USA, and China, as well as, a diagnosis of the institutional problems within the Russian green bond market, and development of recommendations for its advancement.

Methods

The methodological framework of the research is based on a synthesis of institutional analysis, information asymmetry theory, and a comparative approach to the study of regulatory regimes. The empirical foundation comprises regulatory legal acts of the jurisdictions under study, expert assessments from representatives of regulatory bodies and market participants, and proprietary calculations of integral regulatory maturity indicators.

The originality of the proposed Integral Regulatory Maturity Rating (IRMR) is in its fundamental distinction from existing methodological approaches to assessing regulatory systems. The linear indices are based on simple arithmetic averaging of components. They are in use in the World Bank's Doing Business rankings, the Fraser Institute's Regulatory Quality Index (RQI), etc. Otherwise, the IRMR uses non-linear

weighted aggregation accounting for synergistic effects between different elements of the regulatory system.

Modern methodologies for assessing regulatory effectiveness, such as the Heritage Foundation's Index of Economic Freedom or the World Bank's Worldwide Governance Indicators, focus on general regulatory principles; they do not consider the specifics of green finance. The Climate Policy Initiative's methodology is limited to analysing financing volumes without an in-depth assessment of institutional characteristics. The ESG ratings made by Sustainalytics or MSCI agencies concentrate on corporate practices but do not encompass systemic regulatory aspects.

A key advantage of the IRMR is the comprehensive incorporation of seven interconnected parameters of the regulatory system. They utilise exponential coefficients reflecting the non-linear influence of each component on the system maturity. It identifies the bottlenecks within the regulatory structure and facilitates modelling the effects of targeted institutional reforms.

To quantify the qualitative characteristics of regulatory systems, an original methodology for calculating the Integral Regulatory Maturity Rating (IRMR) has been developed. It is based on the weighted aggregation of seven key parameters: Taxonomic Completeness (TC), Stringency of Disclosure Requirements (DR), Mandatory External Verification (EV), Supervision Intensity (SI), Sanctions Rigor (SR), Data Accessibility for investors (DA), and the degree of International Harmonization (IH). The calculation formula is as follows (1):

$$\mathrm{IRMR} = \sum_{i} w_i \times P_i^{\alpha_i} \quad (1)$$

where w_i are weighting coefficients determined by expert ranking;

P_i are normalised parameter values;

α_i are exponential coefficients reflecting the nonlinear influence of parameters on the system maturity.

European Union is the paradigm of normative determinism. The European model for regulating the green bond market is the most comprehensive and institutionally refined system. It is based on the EU Taxonomy (Regulation EU 2020/852), the Sustainable Finance Disclosure Regulation (SFDR – Regulation EU 2019/2088), and the developing European Green Bond Standard (EU GBS) [7].

The EU Taxonomy establishes six environmental objectives and detailed technical screening criteria for seventy-two economic activities. It concerns with the sectors responsible for 0.93 of the region's total greenhouse gas emissions. The “Do No Significant Harm” (DNSH) principle establishes a multi-tiered system of filters. Moreover, it excludes projects with negative externalities even if they make a positive contribution to one of the environmental objectives [8]. An impact analysis on the cost of capital reduces the yield spread of green bonds compared to conventional counterparts by a magnitude of 0.15 to 0.28. It deepens on the issuer's credit rating and the instrument's maturity.

Reporting requirements, codified in the SFDR, mandate the disclosure of sustainability risks and adverse impacts at both the financial product and organisational levels. The Information Density Coefficient (IDC), calculated as the ratio of mandatory disclosure elements to the total number of potentially relevant metrics, stands at 0.87 for the European jurisdiction. This exceeds comparable figures for the United States (0.42) and China (0.63).

The United States has a market autonomy and private certification. The American regulatory philosophy is predicated on the presumption of market mechanism efficacy and the minimisation of direct state intervention. The Securities and Exchange Commission (SEC) confines itself to general requirements for material disclosure under existing securities legislation; it does nor establish specific norms for green bonds [9]. The proposed rule on climate-related disclosures, introduced by the SEC in March 2022, focuses on corporate reporting. However, it does not directly address the issuance standards for green debt instruments.

Within this regulatory vacuum, private certification providers and rating agencies play an important role. The Center for International Climate and Environmental Research (CICERO) has developed the "Shades of Green" methodology. It differentiates projects based on their degree of alignment with the Paris Agreement goals. Vigeo Eiris (now part of Moody's ESG Solutions) provides Second Party Opinions (SPOs) for 0.76 of global green bond issuances. S&P Global Ratings has implemented a Green Evaluation system integrating the

assessments of environmental impact, climate risk resilience, and project governance quality [10].

Empirical analysis reveals significant variability in assessment methodologies: the concordance coefficient between assessments from different providers is only 0.58. It makes an annoying sidelight and complicates the investment decisions [11]. However, this decentralised model stimulates innovation: The Financial Innovation Index (FII) for the green bond segment, measured as the ratio of new structured products to total issuance volume, reaches 0.34 in the US, compared to 0.19 in the EU.

The Chinese Model includes a centralised incentivisation and scaling. China's green bond regulatory system is characterised by a unique combination of centralised planning, a multiplicity of regulators, and active state incentivisation. The People's Bank of China (PBoC), the National Development and Reform Commission (NDRC), and the Ministry of Ecology and Environment form a tripartite regulatory structure with partially overlapping mandates [12].

Updated in 2021, The National Catalogue of Green Finance Projects encompasses two hundred and four categories of economic activity, grouped into six macro-sectors. Notably, until recently, the Chinese taxonomy included "clean coal" and gas power plant projects, reflecting national energy security priorities. The taxonomic convergence coefficient with the European system, calculated as the share of matching categories accounting for technical criteria, stands at 0.71. It demonstrates a gradual alignment of standards [13].

Incentive mechanisms include interest rate subsidies, tax benefits, and priority inclusion in state-owned fund investment portfolios. The State Support Multiplier (SSM) defined as the ratio of the total volume of incentives to the market capitalisation of green bonds. It reaches 0.23 and significantly exceeds comparable figures in developed economies.

Russia and emerging markets have institutional lacunae and growth points. The Russian green bond market is in a stage of institutional formation. It is characterised by a fragmented regulatory framework, a limited investor base, and insufficient integration into global sustainable finance systems. The Government Decree No. 1587 on 21.09.2021 "On the Approval of Criteria for Sustainable Development Projects in the Russian Federation and Requirements for the System of Verification of Sustainable Development Projects in the Russian Federation" established the regulatory foundation. However, practical implementation faces multiple barriers [14].

The national taxonomy of green projects, approved by Government Order No. 1912-p on 14.07.2021, includes twenty sectors and forty-two criteria. They are significantly less detailed than in Europe and China. The Institutional Completeness Index (ICI) aggregates the presence of key elements of regulatory infrastructure. It stands at 0.46 for Russia, compared to 0.52 for Brazil, 0.39 for India, and 0.41 for South Africa.

The verification infrastructure is a limited number of accredited organisations, predominantly affiliated with state structures, creating potential conflicts of interest. The Verification Independence Coefficient (VIC) is calculated as the proportion of verifications conducted by organisations without direct ties to issuers or regulators. It is 0.31; that is critically below the international benchmarks [15].

Table 1 shows comparative indicators of the regulatory maturity of green bond markets in key jurisdictions.

Table 1 – Comparative Indicators of Green Bond Market Regulatory Maturity[1]

Parameter	EU	USA	China	Russia
Taxonomic Completeness Index (TCI)	0.94	0.37	0.82	0.43
Disclosure Rigor Coefficient (DRC)	0.91	0.48	0.69	0.52
Mandatory Assurance Level (MAL)	0.88	0.29	0.76	0.61
Supervision Intensity (SI)	0.86	0.41	0.73	0.38
Restriction Severity (RS)	0.79	0.56	0.67	0.44
Data Availability (DA)	0.92	0.84	0.58	0.49
Alignment with Standards (AS)	0.96	0.77	0.71	0.46

[1] *Indicators are calculated by the author based on expert assessments and normalised on a scale from 0 to 1.*

Parameter	EU	USA	China	Russia
The IRMR Integral Index	0.89	0.53	0.71	0.48

Source: Authors

Analysis of the data in Table 1 reveals significant differentiation in regulatory maturity across jurisdictions. The European Union demonstrates the highest values across nearly all parameters. It shows the systematic approach to formation of a sustainable finance structure. The United States have low scores in formal regulatory metrics coupled with high data accessibility, consistent with its market-oriented model. China occupies an intermediate position, emphasising state regulation while demonstrating relatively low transparency. Russia lags significantly across all parameters, particularly in harmonisation with international standards and supervisory intensity.

Table 2 shows the efficiency coefficients of regulatory mechanisms in key jurisdictions.

Table 2 – The efficiency coefficients of regulatory mechanisms[2]

Mechanism	EU	USA	China	Russia
Information Asymmetry Reduction Coefficient (IARC)	0.87	0.62	0.54	0.41
Investor Confidence Multiplier (ICM)	0.83	0.71	0.66	0.39
Greenwashing Prevention Index (GPI)	0.91	0.44	0.72	0.36
Transaction Cost Coefficient (TCC)*	0.23	0.51	0.38	0.67
Regulatory Elasticity of Supply (RES)	0.76	0.89	0.81	0.42
Market Adaptation Rate (MAR)	0.68	0.94	0.77	0.33

Source: Authors

Table 2 shows the operational efficiency of different regulatory approaches. The European model effectively reduces information asymmetry and prevents greenwashing. However, it has higher transaction costs and slower market adaptation. The American system shows high elasticity and rapid adaptation but provides weak protection against misleading practices. The Chinese approach demonstrates balanced metrics. The Russian system is characterised by systemic dysfunctions across most parameters.

Results

The conducted analysis reveals a fundamental contradiction between the pursuit of regulatory harmonisation and the objective heterogeneity of national financial systems. The European model of comprehensive regulation forms high entry barriers and generates substantial compliance costs. It can hinder market development at early stages. According to the previous research, the excessive regulation leads to a "regulatory choking" effect – the costs of compliance exceed the benefits from reduced information asymmetry [16].

The American approach is based on market self-regulation, and forms a "race to the bottom" in verification standards. Indeed, the competition among SPO providers leads to diminished assessment rigor. Empirical evidence indicates a systematic overstatement of environmental benefits in the absence of mandatory standards [17].

The Chinese model of state dirigisme demonstrates impressive quantitative results but raises questions regarding capital allocation quality and actual environmental impact. The paradox of "green authoritarianism" includes centralised decision-making. It could mobilise resources faster than that of the democratic systems. However, it reduces accountability and transparency.

The critical challenge for Russia is overcoming the institutional gap between formal norms and enforcement practices. Establishing a national verification system without integration with international standards could result in an isolation from global capital flows. At the same time, the strict following to the foreign models without considering the specifics of the national economy could be ineffective (Table 3).

[2] *The lower values indicate higher efficiency for the Transaction Cost Index (TCI)*

Table 3 – Integral assessment of regulatory systems: multidimensional analysis[3]

Assessment Criteria	EU	USA	China	Russia	Emerging Markets (EM) (average)
Institutional Architecture					
Regulatory Centralisation	0.91	0.28	0.87	0.64	0.53
Fragmented Regulatory Landscape	0.24	0.73	0.61	0.82	0.76
Coordination Between Agencies	0.88	0.52	0.69	0.37	0.41
Taxonomic Characteristics					
Criteria Specification	0.93	0.31	0.78	0.42	0.38
Sectoral Coverage	0.89	0.44	0.83	0.51	0.46
Technical Stringency	0.96	0.38	0.74	0.39	0.34
Dynamic Adaptability	0.71	0.92	0.66	0.48	0.52
Information disclosure mechanisms					
Mandatory Pre-issuance Reporting	0.94	0.41	0.81	0.56	0.47
Standardisation of Post-Issuance Reporting	0.92	0.36	0.77	0.44	0.39
Data Update Frequency	0.87	0.78	0.62	0.38	0.43
Machine-Processable Formats	0.83	0.91	0.54	0.29	0.31
Verification Infrastructure					
Accreditation of Verifiers	0.89	0.46	0.79	0.61	0.44
Independence of Assessment	0.86	0.88	0.52	0.31	0.37
Methodological Unification	0.91	0.27	0.73	0.54	0.42
Responsibility for Misrepresentation	0.84	0.68	0.71	0.36	0.38
Supervisory Practices					
Proactive Monitoring	0.88	0.33	0.76	0.41	0.36
Risk-Based Approach	0.79	0.86	0.58	0.32	0.39
Cross-Jurisdictional Cooperation	0.92	0.74	0.47	0.24	0.33
Sanctions Regime					
Gradation of Penalties	0.87	0.62	0.72	0.48	0.41
Inevitability of Enforcement	0.81	0.71	0.68	0.34	0.37
Reputational Consequences	0.93	0.89	0.56	0.42	0.44
Market Incentives					
Tax Incentives	0.62	0.44	0.91	0.53	0.57
Regulatory Preferences	0.74	0.31	0.86	0.47	0.49
Institutional Demand	0.88	0.83	0.77	0.38	0.42
Integration with Global Standards					
Compliance with the ICMA GBP	0.97	0.91	0.73	0.51	0.48
Recognition by CBS	0.94	0.76	0.67	0.43	0.41
Participation in the IPSF	0.98	0.22	0.88	0.19	0.36
Composite Indices					
Regulatory Complexity (RC)	0.91	0.48	0.74	0.49	0.44

[3] *All indicators are normalised on a 0-1 scale based on the author's methodology of weighted aggregation using nonlinear coefficients. Emerging markets include averaged data for Brazil, India, Mexico, South Africa, and Indonesia.*

Assessment Criteria	EU	USA	China	Russia	Emerging Markets (EM) (average)
Market Efficiency (ME)	0.72	0.93	0.78	0.41	0.46
Institutional Stability (IS)	0.88	0.69	0.71	0.38	0.42
The IRMR Integral Maturity Index	0.89	0.53	0.71	0.48	0.43

Source: Authors

Detailed analysis of the presented matrix of regulatory characteristics reveals key divergences between jurisdictions. The European Union demonstrates the highest degree of institutional maturity with a coefficient of 0.89. It attributes to the comprehensiveness of its regulatory framework and a high degree of integration with international standards. However, it has lower dynamic adaptability (0.71) and market efficiency (0.72), and indicates potential risks of regulatory rigidity.

The American model has minimal centralisation (0.28) with maximum market efficiency (0.93) and dynamic adaptability (0.92). It forms favourable conditions for financial innovation but reduces protection against opportunistic market behaviour. Particularly critical is the low level of methodological unification in verification procedures (0.27). It generates substantial variability in the assessment of bond "greenness".

The Chinese system is on a median position on most parameters. It demonstrates a unique combination of high centralisation (0.87) with developed fiscal incentive mechanisms (0.91). However, low indicators for verification independence (0.52) and cross-jurisdictional cooperation (0.47) limit the international recognition of Chinese green bonds.

The systemic imbalances of the Russian regulatory system have a relatively high multiplicity of regulators (0.82). However, it is not compensated for by effective coordination (0.37), and resulted in its fragmentation. Critically low levels of cross-jurisdictional cooperation (0.24) and participation in international platforms (0.19) provide an isolation from global sustainable finance flows.

Emerging markets demonstrate problems similar to Russian ones. However, they have higher indicators of fiscal incentives (0.57) and institutional resilience (0.42). It shows their potential development.

Analysis of composite indices should be considered with a particular attention. Regulatory complexity shows the comprehensiveness and detailing of the regulatory framework. It is highest in the EU (0.91) and lowest in the US (0.48). It confirms fundamental differences in countries regulatory policies. Market efficiency measures the system's ability to generate innovation and minimise transaction costs. It shows an inverse relationship: the US scored 0.93; the EU scored 0.72. It shows a trade-off between regulatory stringency and market dynamism.

Institutional resilience characterises the system's ability to withstand external shocks and maintain participant trust. Explained by its developed enforcement mechanisms and reputational effects, it is the highest in the EU (0.88). Russia has a critically low level (0.38) and establish risks of systemic instability in conditions of global volatility.

Russian regulation of the green bond market is in a process of evolutionary development and has a lot of institutional challenges. The Bank of Russia plays a coordinating role, publishes recommendations on responsible financing, and develops ESG risk assessment methodologies. The Ministry of Economic Development controls the development of the national taxonomy and green project criteria. VEB.RF is a methodological center and the largest issuance arranger.

Established in accordance with Government Decree No. 1587, the national verification system is a two-tier structure: project verifiers and accreditation bodies. Nowadays, seven verifiers have been accredited – primarily consulting companies and rating agencies. However, the lack of clear methodological standards and independence criteria form the risks of conflicts of interest and undermines the confidence of international investors.

Fiscal incentives are limited to subsidising coupon income for specific issuer categories under VEB.RF programs. The absence of systemic tax benefits and regulatory preferences reduces the attractiveness of green bonds compared to traditional instruments. The Green Bond Relative Yield Coefficient (GBRYC) is calculated

as the ratio of risk-adjusted returns of green bonds to conventional bonds. It considers all forms of state support, and stands at 0.94 for Russia, indicating insufficient incentives.

Information infrastructure is characterised by fragmentation and low data accessibility. The lack of a centralised platform for disclosing information on green projects complicates monitoring the use of proceeds and assessing environmental impact. The Information Transparency Index (ITI) aggregates data availability, completeness, and verifiability. It is significantly below the level of developed markets and scored 0.41.

Development prospects for the Russian green bond market require the comprehensive institutional modernisation. The priority areas are harmonising the national taxonomy with international standards in terms of Russian economy specifics; establishing an independent verification infrastructure with clear accreditation and accountability criteria; developing a system of fiscal and regulatory incentives ensuring the economic attractiveness of green instruments; formation of a centralised disclosure platform with machine-readable data formats; intensifying participation in international sustainable finance initiatives and platforms.

Conclusions

Thus, the research formulates a number of fundamental conclusions regarding the nature and evolution of regulatory regimes in green bond markets.

Firstly, a paradox of regulatory effectiveness has been identified. An increase in regulatory granularity and stringency leads to a non-linear rise in transaction costs. It begins to negatively impact market development. The optimal balance between regulatory stringency and market efficiency varies depending on the institutional maturity of the financial system and the level of development of self-regulatory mechanisms.

Secondly, a convergence dilemma has been identified. The pursuit of international standard harmonisation has many differences in terms of the economic structures, legal traditions, and political priorities. The unification without considering national specificities could result in the institutional rejection and the formation of "grey" markets.

Thirdly, the critical role of verification infrastructure as a mediator between regulatory requirements and market practices has been established. The independence, competence, and accountability of verifiers determine the level of trust in green bonds to a greater extent than the formal stringency of regulation.

Fourthly, an asymmetry between the development of the regulatory framework and enforcement mechanisms in emerging economies has been revealed. Establishing of the institutions could result in a gap between de jure and de facto regulation, undermining market participants' trust.

The scientific novelty of the research is the development of an integral model for assessing regulatory maturity (IRMR). It quantifies the qualitative characteristics of regulatory systems and facilitates cross-country correlations. The proposed system of non-linear weighting coefficients shows the synergistic effects between different regulatory components and identifies the institutional imbalances.

The practical significance of research results is in their potential application in formulating national strategies for the development of green bond markets. For Russia, it is critically important to avoid both copying of foreign models and the formation of an isolated national system. The optimal strategy involves the selective adaptation of best international practices in terms of Russian economy specifics, and a gradual integration into the global sustainable finance structure.

Further research will focus on the dynamic aspects of regulatory regime evolution, the feedback mechanisms between regulation and market innovation, and the development of adaptive regulatory frameworks to evolve in response to changes in the technological and institutional context.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR'S CONTRIBUTIONS

Marina G. Kovtunenko – conceptualization; supervision.
Arseny A. Kolomytsev – writing – original draft.
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The portfolio technology as competitive tool of personal branding development

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ORIGINAL ARTICLE

Abstract. The increasing competition in the labour market emerged the problem of graduates' adaptation. The education system helps to live and work effectively in a rapidly changing world. Nowadays, the major purpose of education is personal, social, and professional competences. Indeed, the ability of the graduates to analyse and effectively use information is one of the most demanded. Therefore, an independent work of the students takes a significant place in the curricula of higher education institutions. However, to be competitive in the labour market is the one urgent task of the modern education. The purpose of this study is to determine empirically the effectiveness of portfolio technology for personal branding development in terms of competitiveness. Indeed, the process of personal branding development is relevant since the employment of graduates is included in the university's accreditation indicators. Despite the portfolio technology has been introduced into the higher education system, according to our research, it does not achieve its goals. The reason is the formal and unjustified attitude of the education system towards the technology. However, our research shows a high ranking of motivation to master self-presentation skills, professional career, etc. Therefore, there is a need to address this contradiction through the effective management. The sociological survey method allows us to describe the process under study and identify the difference between educational institutions. Indeed, the skill of personal portfolio development depends on the objectives of the educational process at the university. Moreover, many students are not informed about the portfolio technology. We possess it a result of insufficient management in terms of personal brand development. In general, according to research results, mastering of portfolio technology as a tool for personal branding and competitiveness is quite poor.

Keywords: portfolio technology; personal competition; personal branding; self-presentation; professional community

JEL codes: A14

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Introduction

Indeed, two trends in the labour market define the studying of personal branding and portfolio as a competitive tool.

- firstly, the growing competition for jobs and demands of employers;
- secondly, the development of digital technologies for self-presentation and business contacts.

Modern digitalisation increases the level of competition within professional community. Indeed, social media provides new opportunities for employees. Nowadays, they can choose the mode of work: on-line or off-line. Therefore, the competitiveness within the professional communities increased. Moreover, some professional communities capitalise their professionalism. For example, doctors of narrow specialisation having developed a personal brand usually involved into the pais health care; teachers became popular tutors;

design engineers establish personal design bureaus, etc. All mentioned above form the competitiveness requiring the skills of self-presentation.

Therefore, it is necessary to determine the concept of brand. The term was borrowed from marketing and business industry and its main definitions are related to the concepts of a trademark. According to Mazilkina E.I., brand is a promoted trademark or image resulting from various marketing efforts [9, p. 11]. O.G. Vazhnova suggests two types of definitions of brand concept. Firstly, there are individual attributes: the name, logo, and other visual elements (fonts, design, colour schemes, and symbols) to distinguish a company or product from competitors. Secondly, it is the image and reputation of a company, product, or service for the customers and partners [3, p. 8]. Knyazeva M.A. possesses brand as a trademark characterised by a certain perception on the part of the target audience [8, p. 67]. According to the educational literature, brand can be understood as the reputation, image, and recognition of a trademark to distinguish from competitors for the consumers of goods and services. It is relevant to the production of goods or the provision of services by legal entities. Therefore, many people percept the term brand as corporate brand or company brand. However, development of opportunities for individuals allows them to capitalise their professional achievements throught their skills, image, and reputation. It provides the introduction of personal brand concept. The concept of a personal brand is developing. According to Zeynelova A.E., a personal brand is the perception of a person by the others [6, p. 18]. The personal brand is becoming widespread within professional communities. It concerns with the desire of publicity, provided by expanding personal presentation through the social networks. A personal brand is a public image of a person in a particular niche, i.e. medicine, education, beauty, business, art, etc. Nevertheless, it is not necessary to be a certified specialist; it is more important to have an experience and charisma. Today, consumers critically consider any advertising activity and mostly focused on a specific person. It provides the prevalence of the personal brand over the company one because of competition. Teamwork and personal characteristics are a priority to select specialists in any field. The crisis economy requires businesses to reduce costs. As a result of optimisation, only highly competitive specialists having the ability to attract attention to themselves remain in the staff. Along with this, they attract attention to the company and increase the value of company product or service. Personality becomes primary one [4, p. 50].

The modern interpretation of personal brand concept is the image and reputation of a particular person and consumer expectations on the service provided. Moreover, a personal brand is closely related to its personal socially significant qualities, the service provided or the product itself [11, p. 91]. The brand's reputation itself allows consumers of services to wait for the quality and professionalism [5, p. 50].

Therefore, in modern competitive economic conditions, the demand of employers is growing and changing towards assessing the applicant's level of competence rather than basic education. Hence, the issue of professional personal positioning is becoming particularly relevant.

Methods

One of the most effective tools to compete and show ones' competence is a portfolio. It is an opportunity to demonstrate achievements in a particular field of activity and impress a potential employer. The formation of a new trend trough the presentation of personality in various fields of professional activity acquires portfolio management skills. With the transition to the Bologna process, Russian universities introduced the requirement to keep a portfolio for each student. Working with a portfolio in a practical, professional, and socio-educational environment contributes to the development and assessment of students' competencies. It allows graduates to develop their professional qualities, and effectively present their achievements to future employers [13, p. 138].

Many Russian scientists studied a professional portfolio and its role in the development of personal competitiveness. A.G. Asmolov researched issues of personal and professional development related to the portfolio as a tool of self-presentation [1]; V.A. Bolotov developed the methodological basis of the portfolio as a tool for evaluating professional achievements [2]; I.A. Zimnaya studied issues of professional competence and its reflection in the portfolio [7]; N.F. Radionova investigated the role of the portfolio in the system of professional development of a teacher [14].

The concept of a portfolio, as a business card of an individual or an organisation, has gained importance with increasing of competition in the labour market. To attract the attention of employers or clients, employees collected samples of completed works or certificates of achievements in the profession. Initially, it was a kind of dossier.

The idea of using a portfolio in education is widespread and to be actively applied in Russia with the transition to the Bologna process. It began to develop the technology of graduate competitiveness as a result of a student's activity after completing a certain educational stage and preparing for future professional activity. In this regard, the development of the concept began within the framework of pedagogical science.

The Russian specialists have different approaches to the definition of the concept of portfolio. For instance, Stefanovskaya T.A. considers the technology of portfolio as the organisation of the pedagogical process, a set of actions improving the relationships between the components of the pedagogical process in accordance with a certain theoretical paradigm [15].

Selevko G.K. defines portfolio technology as a system of constituent components of the pedagogical process, based on a scientific basis and contributing to the achievement of the intended results [16].

D. Meyer considers portfolio technology as a purposeful product and a collection of students' works, demonstrating their efforts, progress, achievements [10].

Subsequently, the concept was transferred to the higher professional education. Nevertheless, the term portfolio is widely used in many areas of human activity and has a large number of definitions and characteristics. However, there is no generally accepted interpretation of this concept yet. Nowadays, the Russian educational system understands this term as a folder of individual achievements.

Nevertheless, portfolio technology allows student to accumulate and competently evaluate the personal educational results for special periods of studying. It includes diplomas and other papers on specific results achieved by students in various events, contests, etc. According to this particular approach, portfolio motivates the student’s activity, develops productive learning skills, encourages students' activity and independence, expands educational opportunities and self-education, etc.

Therefore, economic situation requires changing of the labour market. It provides qualitatively reconsideration of graduates professional activity. The priority moral and psychological qualities of a successful employee are initiative and independence, creativity, the ability to cooperate, high motivation for professional development and career growth. It provides the mobility and competitiveness of the employee. Hence, the portfolio technology is an effective tool for assessment a person in terms of his or her professional or educational activity. However, it is necessary to study the issue of the portfolio technology empirically in the higher professional education system.

Results

This research is a continuation of the analysis results. The purpose of the research was to determine the structure of university students' competitiveness, empirical substantiation of ways to improve the quality of personal competition skills, willingness to build a professional activity strategy in accordance with the objectives of the university's educational process. The beginning of the research was published in a Journal "The structure of students' personal competitiveness as a determinant of the formation of educational process objectives of an educational institution" [12].

The study was conducted using a Google form survey; a total sample size was 600 people. The object of research is students of Yaroslavl State Technical University (YSTU) (1-4 year of Bachelor's degree; 1-2 year of Master's degree; all the institutes); Kostroma State Agrarian Academy (KSAA) (1-4 year of Bachelor's degree; Economics faculty).

The sociological survey method allows us to determine the proportion of respondents with the different skills to form a personal portfolio. The results obtained show the difference in students' preparation for using portfolio as a personal competitiveness tool.

Table 1 – Proportion of YSTU and KSAA students with personal portfolio management skills (% of respondents)

Privacy Strength	YSTU	KSAA
Yes, I am always careful about its content	5.5	5.1
Yes, I am not always careful about its content	27.5	59.0
No, I am not careful about its content	45.3	28.2
I do not know what it is	27.5	7.7

Source: Authors

Indeed, the research results are as follows:

- the development of personal portfolio management skills depends on the objectives of the university's educational process;
- the proportion of the students interested in developing personal brand skills is quite low for both universities;
- there is a significant difference in the number of the students considering personal brand skills unnecessary (the share of those in both university is quite high); it confirms the role of the educational institution;
- many students are not informed about the portfolio technology. We possess it a result of insufficient management in terms of personal brand formation and development;
- in general, according to research results, mastering of portfolio technology as a tool for personal branding and competitiveness is poor.

The trends of rapid production renewal in modern conditions determine the high demands on the new generation of specialists. It requires the students' activity, independence, flexibility, non-standard thinking, general and professional culture. Indeed, earlier, the purpose of education was the formation of the knowledge, skills, and qualities of a person necessary for work. Nowadays, specialist training involves the development of personality qualities relevant to achieving success in any professional activity.

However, an employment of the university graduates requires the development of the job selection criteria.

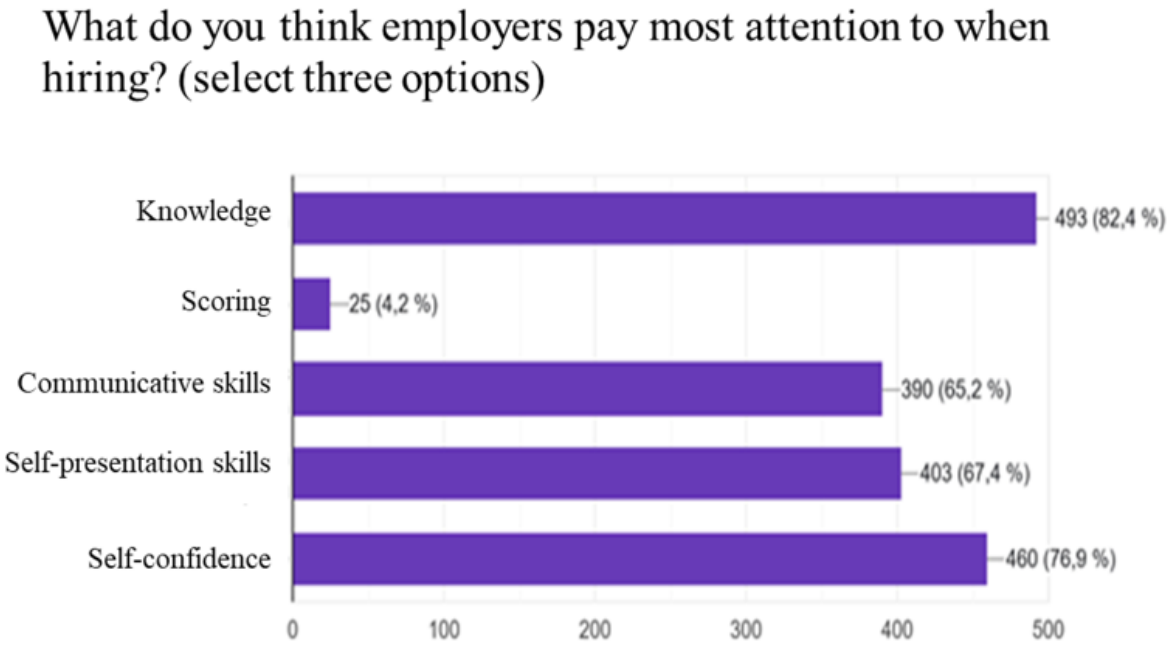

Figure 1. YSTU students' views on the job selection criteria (% of the respondents)

Source: Authors

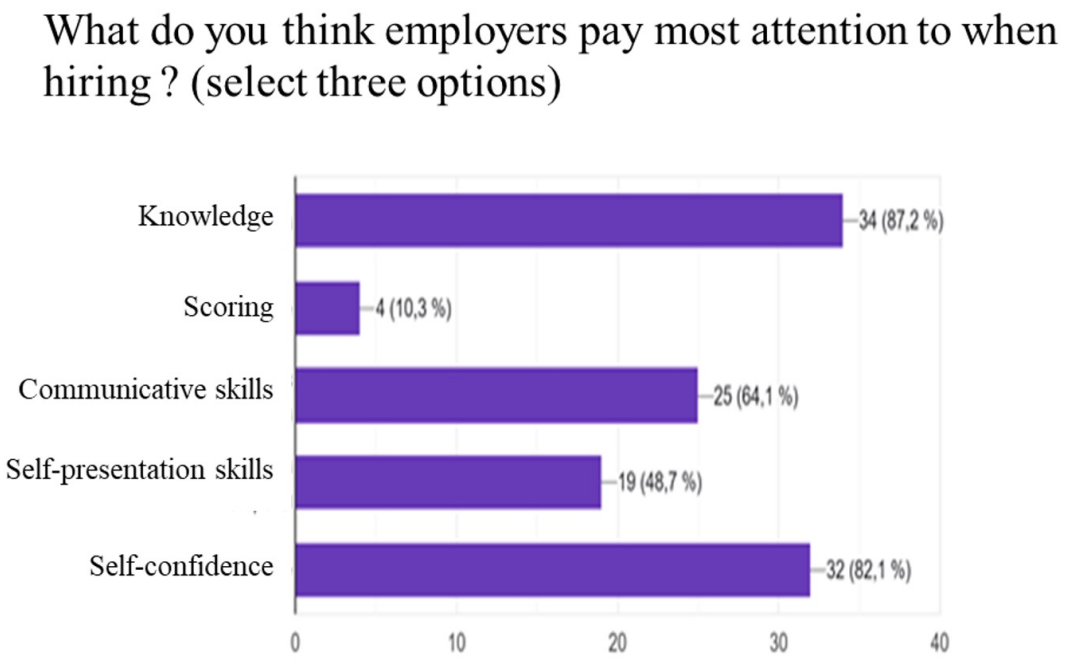

Figure 2. KSAA students' views on the job selection criteria (% of the respondents)
Source: Authors

According to the comparative analysis, there is a difference in the assessment of criteria such as "diploma grades": 4.2% versus 10.3% and "self-presentation skills" 67.4% versus 48.7%. It may indirectly indicate differences in local labour markets. However, to contradict knowledge, skills, and abilities to the personality qualities requires the achievement of success in the professional activity. To address the problem, the following question was asked:

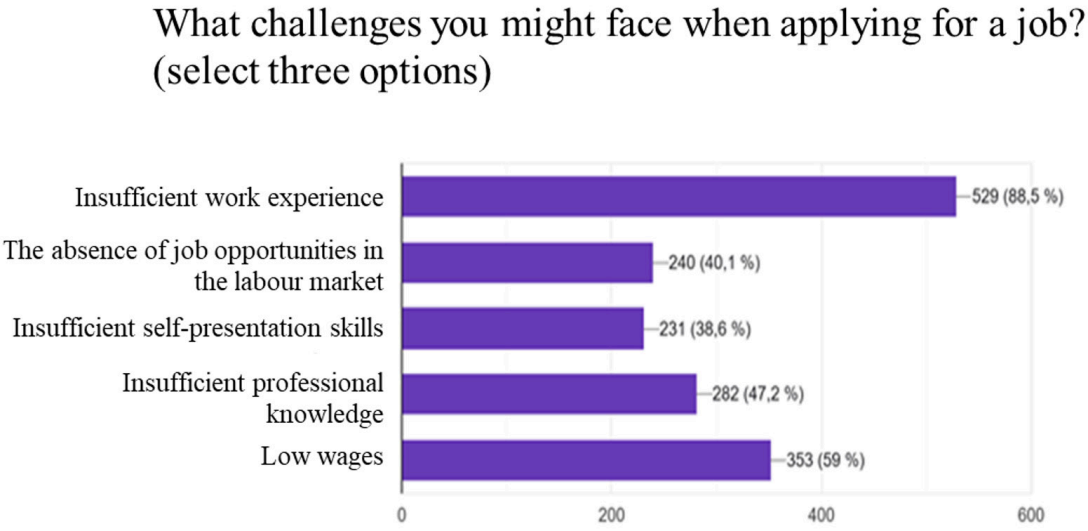

Figure 3. YSTU students' assessment of difficulties in employment (% of the number of respondents)
Source: Authors

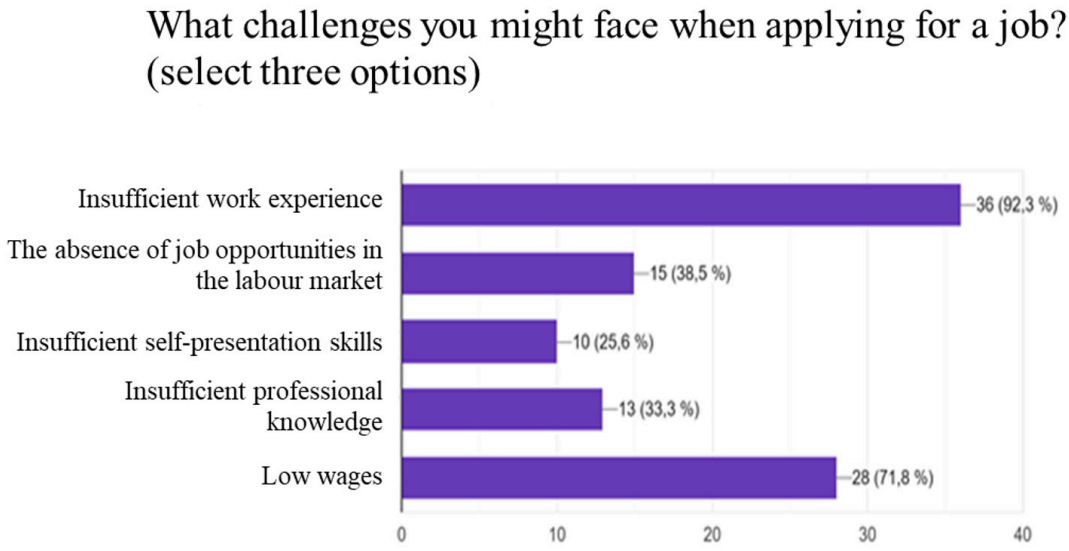

Figure 4. KSAA students' assessment of difficulties in employment (% of the number of respondents)
Source: Authors

To the question: "How do you assess the level of competition for young professionals in the labour market in your city?":

Table 2 – Respondents' assessment of the level of competition in the local labour market (% of the number of respondents)

Assessment	YSTU	KSAA
The competition is high, it is difficult to get a job in the specialty	52.2	47.8
The competition is not very high, it is not difficult to get a job in the specialty	48.7	51.3

Source: Authors

The results of the study revealed a significant contradiction since the higher education system ignores the possibility of using the portfolio methodology as a tool for personal competitiveness. According to the study, 94.3% of YSTU students and 86.8% of KSAA students consider important the professional and career growth. To the question: "Which of these personal qualities would you like to develop for yourself, since you are not good enough at it yet?"

The ability to show oneself needs to be developed chose 73.5% of YSTU and 55.2% of KSAA students.

Conclusion

Nowadays, on the competitive labour market, having a portfolio is of particular importance to increase one's competitiveness. A portfolio is a collection of works, achievements, and projects demonstrating a specialist's professional skills, experience, and personal qualities.

One of the key advantages of a portfolio is the opportunity to demonstrate real examples of the achievements and competencies to potential employers or clients. The portfolio as convincing evidence of the candidate's competence and reliability in the conditions of high competition in the labour market.

In addition, the portfolio promotes personal and professional development. Regularly updating of a portfolio helps to track professional growth, analyse achievements, and set new goals. It allows the specialist to be competitive in the labour market and ready for new challenges.

In the education, the portfolio also establishes the competitiveness of future specialists. In universities, a portfolio in a special professional, and socio-educational practice for development and assessment of students' competencies. This allows graduates to develop professional qualities, and effectively present their

achievements to future employers.

The effectiveness of a portfolio as a competitive tool is determined by following factors: firstly, it is the relevance of portfolio materials; secondly, it has a clear structure and logical presentation of information; thirdly, the portfolio shows the professional growth and development. A portfolio is a fashion trend, and a necessary tool of a modern professional. It ensures a career development, establishes business contacts, and increases graduates' personal value in the labour market.

However, an empirical study conducted at two universities revealed the ineffective use of this tool for building a personal brand and competitiveness. Despite of motivation to develop self-presentation skills, and a desire to pursue a career in the profession, practice of using portfolio technology does not achieve its goals.

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The work was done on a personal initiative.

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The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

Irina V. Popova – writing – original draft.
Marina B. Abramova – data curation, formal analysis, validation.
Alexey V. Zorin – conceptualization, project administration, writing – review & editing.

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Digital twins as a tool to increase the efficiency and sustainability of the agro-industrial complex

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ORIGINAL ARTICLE

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Abstract. This article examines the applicability and impact of digital twin technologies across the agri-food sector, from field operations to postharvest logistics. Building on a structured review of recent literature and industry cases, we synthesize how physics-based and data-driven twins integrate sensing, IoT, and AI to enable real-time monitoring, scenario analysis, and decision support. We classify agricultural digital twins into four functional groups – crop and livestock production, machinery and maintenance, postharvest handling, and supply-chain coordination – and map them to key performance indicators such as yield stability, resource efficiency, quality preservation, and risk reduction. The analysis identifies consistent benefits, including improved input use, earlier anomaly detection, and more resilient planning under weather and market uncertainty. However, adoption is constrained by data quality and interoperability issues, high initial costs, skills gaps, and unresolved concerns around cybersecurity and governance. We propose a staged implementation framework that prioritizes high-value use cases, lightweight edge analytics, and open data standards, accompanied by a governance model for data sharing. The article contributes a practical roadmap and a set of evaluation metrics that link digital-twin capabilities to farm-level and supply-chain decisions. Limitations relate to heterogeneous evidence and context specificity. Future work should explore integration with generative AI, privacy-preserving learning, and cross-farm platforms.

Keywords: digital twins; agrotechnology; digitalisation of agriculture; precision agriculture; virtual farm models

JEL codes: Q16, Q55, O33

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Introduction

Agriculture is one of the key sectors of the global economy. Nowadays, population growth, climate change, soil degradation, lack of water resources and qualified personnel are the threats to the sustainable development of the industry. According to the Food and Agriculture Organization of the United Nations (FAO), by 2050 the world's population will increase to almost 10 bn people[1]. In a scenario with moderate economic growth, such population growth rates will cause an increase in global demand for agricultural products by 50-60% compared to current level. It will degrade the natural resources. Moreover, already every 11 people in the world are hungry; according to an average estimate there are more than 735 mln of people. Therefore, the digital transformation of agriculture is becoming a prerequisite for ensuring food security and sustainable development.

Digital twins are innovative technologies of Industry 4.0. They allow us to optimise the agricultural processes, increase yields, conserve water, fertilizers, and energy, etc. [2]. However, the issue is understudied, especially for the developing countries.

The purpose of this work is to assess the opportunities and risks of digital twins in agriculture. Moreover, we emphasise on increasing of available resources efficiency and sustainability of agro-industrial production

[1] *Food and Agriculture Organization of the United Nations. (2018). The future of food and agriculture – Alternative pathways to 2050. FAO. Source: https://openknowledge.fao.org/server/api/core/bitstreams/e51e0cf0-4ece-428c-8227-ff6c51b06b16/content (accessed on 01.04.2025)*

through optimising processes, reducing costs, and minimising environmental threats. Our research focuses on the economic component of digital twins' implementation. The article focuses on the main areas of digital twins' application, provides practical examples, and discusses their key issues.

Many domestic and foreign scientists considered the development and implementation of digital twins in terms of productivity, sustainability, and transformation of agriculture. They are as follows: G.A. Getz [2], A.S. Dorokhov [1], L.O. Velikanova [12], A.V. Zharinov [15], I.A. Panteleev [7], S. Kim [4], W.J. Knibbe [5], X. Han [3], Y. Yin [14], D. Onwude [6], C. Pylianidis [8], etc.

Indeed, scientific literature consider a digital twin as a tool to increase the efficiency and sustainability of agricultural production. W.J. Knibbe [5] and X. Han [3] highlight successful applications of digital twins for optimising greenhouse microclimate and animal health monitoring. S. Kim [4] and Y. Yin [14] examines the possibilities of individualised agricultural management and predictive machine maintenance. D. Onwude [6] and C. Pylianidis [8] focuses on its environmental aspects and sustainable development issues.

The methodological basis of the study was a systematic approach, a method of comparative analysis, modelling, and forecasting. During the research we analyse statistical data, analytical materials, FAO reports, reports on the development of digital technologies, case studies in peer-reviewed international journals, etc.

Main part

Characteristics and concept ofthe digital twin

Digital twins are digital models of a physical objects or systems providing a connection between a physical object in reality and its virtual model. This technology is a part of Industry 4.0 based on the collection and analysis of data from sensors and other sources to simulate various processes and scenarios, forecast, and make optimal decisions [1]. It allows ones to simulate activity of the physical object and help to save time, money, avoid many risks associated with the implementation of various changes in the environment [15].

Digital twins can be classified in term of their purpose and level of complexity. The first type is a prototype (Digital Twin Prototype, DTP); it is used at the design and development stage and contains all the information to create a physical object, including geometric, structural, and technological models. DTP allows ones to optimise and test a product before its physical implementation, reduce risks and production costs. For example, in agriculture, DTP can be used to design new models of agricultural machinery or plan farm infrastructure.

The second type is a Digital Twin Instance (DTI); it is developed for a specific physical object and accompanies it throughout its life cycle. DTI collects data on the condition of the facility, its operation, repairs, and replacements. It allows it to monitor its performance and make decisions about necessary activity. In agriculture, those monitor the condition of agricultural machinery, animals, and plants.

The third type is an aggregated twin (Digital Twin Aggregate, DTA); it combines data from multiple digital twins for managing the objects and systems. In agriculture, those manage several fields or farms through analysis of soil, yields, and climatic conditions to optimise resources and development of various strategies.

The main components of a digital twin include three key elements: data collection, modelling, and application. Digital twins use four key technologies ensuring real-time data collection, storage, analysis, and design of physical objects digital representations.

Internet of Things (IoT) forms an extensive network connecting objects, people, or their combinations. Indeed, various types of wireless sensor networks are used to collect data from physical objects. It allows ones to design digital copies for analysis, manipulation, and optimisation.

Cloud computing provides digital twins with the necessary computing resources and storage capabilities. This technology helps digital twins to store extensive data in the cloud and access the necessary information. It effectively reduces the computing time of complex systems and solves the problems associated with storing large amounts of data.

Artificial Intelligence (AI) helps to analyse data, formulate recommendations, forecast system behaviour, and propose strategies to prevent potential problems. Key areas of AI include machine learning, computer

vision, natural language processing, etc.

Augmented Reality (AR/VR/MR) combines physical and virtual reality. Virtual (VR), augmented (AR), and mixed reality (MR) are subdomains included in the broad term of augmented reality. AR imposes digital information on real objects; VR and MR designs virtualised or hybrid environments for interacting with a model object.

The development of technology provides digital twins to be more complex and multifunctional. Modern digital twins can integrate data from a wide variety of sources, such as satellite imagery, meteorological data, and IoT devices. It provides modelling of various complex systems. In addition, with the development of machine learning and artificial intelligence technologies, digital twins can analyse current data, independently offer solutions to optimise processes, etc. [7].

Therefore, digital twins are increasingly being used in agriculture and forestry, animal husbandry, energy, construction, manufacturing, transport, logistics, healthcare, etc. According to MarketsandMarkets forecast, the global digital twin market will grow from 10.1 bn USD in 2023 to 110.1 bn USD by 2028, with an average annual growth rate of 61.3% over the forecast period[2].

The use of digital twins in agriculture

In agriculture, different types of digital twins are widely used. They optimise work processes and increase the efficiency of enterprises. Moreover, they design dynamic real time virtual models of physical agricultural objects, plants, animals, fields, or ecosystems. Using data from various sources such as sensors and IoT devices, satellites, drones, and weather stations, digital twins provide a deep understanding of current processes and help accurately manage agricultural operations. These models show the real state of objects, forecast their development by modelling of various scenarios using advanced algorithms, including machine learning technologies.

Precision farming is one of the key applications of digital twins. They allow farmers to simulate different crop scenarios, taking into account the soil type, climatic conditions, humidity levels, and nutrient availability to make efficient decisions for planting, watering, harvesting, management, etc.

For example, the practical application of digital twins in the tangerine orchards on Jeju Island, South Korea. According to Nature Communications Journal, scientists have developed and implemented a digital twin covering more than 185,000 hectares of tangerine plantations across the island. The system combines data from IoT sensors, satellites, open weather sources, and other digital platforms. The digital twin made it possible to track changes in the microclimate and plants, forecast yields with high accuracy.

The digital model achieved 89.6% accuracy in crop forecasts. It reduces crop losses and water consumption by 17% and 23%, respectively. Indeed, it optimises logistics and storage costs and decreases the associated costs by an average of 12% [4].

Therefore, digital twin is a tool for individualised agricultural management in terms of the specifics of zones. It ensures productivity and more sustainable resource management.

The resource management is an important aspect of digital twins' application. These technologies provide more efficient use of water, fertilizers, and various chemicals by monitoring soil and plant conditions. It significantly reduces waste, costs, and increases the sustainability of agriculture.

Willem Jan Knibbe described the use of a digital twin in greenhouse crop production in the Netherlands. The study presents a digital twin integrating data from sensors, climate models, and parameters of plants to optimise the management of microclimates in greenhouses. As a result, producers managed to reduce water consumption by 20-25%; increasing fertilizer efficiency by 18%. Moreover, modelling plant growth and automatically controlling environmental parameters (lighting, temperature, oxygen levels, etc.) increase tomato yields by 11% without increasing energy and chemical costs. It reduces the burden on the environment and provides the sustainable development of agriculture [5].

In animal husbandry, digital twins are used to monitor animal health in real time. Sensors installed on

[2] *Markets and Markets. Digital Twin Market Size, Share & Industry Trends Growth Analysis Report by Application, Industry, Enterprise and Geography – Global Growth Driver and Industry Forecast to 2028. Source: https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html (accessed on 12.03.2025)*

animals collect data on their movement, behaviour, body temperature, and other physiological parameters. These data are transferred to a digital model analysing and identifying deviations from the norm to explore the health problems at an early stage.

For example, China has developed a digital twin model for cattle monitoring. The study used IoT sensors installed on animals to collect data on their body temperature, activity level, behaviour, and other parameters. These data were transferred into a digital model based on deep learning algorithms. The model analysed animal behaviour and detected deviations from the norm in real time. The system achieved an accuracy of 94.97% in classifying animal behaviour. It increases significantly the timeliness of disease detection and reduces losses. The model was successfully used to monitor 120 heads of cattle for 30 days, demonstrating high reliability and scalability [3].

In addition, digital twins are used in the management of agricultural machinery. The analysis of data from tractors and other machines provides predictive maintenance. It prevents breakdowns, reduces downtime, and increases the service life [11].

For example, the development of a digital twin for the Lovol GM100 combine harvester. The study implemented a lightweight digital twin system simulating both the structure of the machine and the complex kinematic relationships between its key components. One of the key elements of the system was an intelligent fuel consumption forecasting model based on the LightGBM gradient boosting algorithm based on data received from sensors in real harvest conditions.

The system covered a variety of parameters, including driving speed, transmission load, and current fuel consumption. Special attention was paid to maintaining the correct transmission of the physical behaviour of the combine units in real-time conditions. According to the field tests, the fuel consumption of forecasting system under full load conditions reaches an average error is 0.24 l/h; a maximum error is 0.84 l/h; an average relative error is 1.09% [14].

It provides the reduction of maintenance and fuel costs. Moreover, the implementation of predictive analytics helps to make technical and managerial decisions based on machine behaviour.

Moreover, the transportation, drying, cooling, and storage of agricultural products can also be optimised through using digital twins. The technologies enable real-time monitoring of the supply chain. It increases its reliability and sustainability.

Monitoring of data on temperature and humidity in the warehouse prevents a spoilage and increases a duration of products by using digital twins. Indeed, a digital warehouse twin can analyse temperature and humidity data to make timely adjustments and prevent losses.

To analyse and optimise the storage and transportation conditions of fresh cucumbers, eggplants, strawberries, and raspberries the scientists of Swiss Empa laboratory designed a digital twin. The programme organised the temperature and associate it with a loss of product quality based on measuring air temperature data. The study analysed 95 shipments in the cold chain from Spain to Switzerland. According to the results, reducing the storage time at the distribution centre by just one day increased the quality of the fruit quality index by 18% for cucumbers and eggplants and by 60% for berries. Reducing the temperature during shipment by 5°C extended duration of strawberries by an average of 36%, and raspberries by 73%. In addition, a 10% increase in relative humidity during transportation and storage reduced weight loss for all fruits studied by 20% [9].

Therefore, use of digital twins can significantly improve the efficiency of post-harvest processes, reduce product losses, and increase the quality of fruits supplied.

Generally, digital twins help model market demand and supply in accordance with the market needs. It reduces the excess production and associated costs and increases the profitability of agricultural enterprises [12].

Moreover, the technology is also used for environmental monitoring and compliance with regulatory requirements and standards. Digital models (twins) help to model and monitor parameters of greenhouse gas emissions, chemicals, soil, water, etc. It ensures quickly responding to deviations from the norm and developing measures to reduce the negative impact of agricultural activities on the environment.

One of the most significant domestic examples of digital twin technologies is Russia's largest agricultural holding Rusagro Group of Companies, Russia. The company actively uses digital twins in various segments of business, including logistics, processing of agricultural products, and crop production.

The latter uses digital field containing information about the electronic boundaries of passive zones, the history of crop cultivation, soil indicators, and the results of technological operations. It optimises the use of machinery, forecasts and monitors harvesting, etc. To plan farming rotation, Rusagro designed a digital product. It analyses more than a million scenarios for each field with a planning horizon of up to 10 years, considering chemical composition of the soil, potential yields, and market conditions.

In the fat and oil business, Rusagro designed digital twins of its oil extraction plants and raw material management models based on the Digital Farmer platform. It optimises logistics, reduces transportation costs, and improves raw material management. Based on LLamasoft Supply Chain Guru, the company has developed a tactical model for 1 year, focusing on the sunflower harvest season, and designed an operational model with a next day planning horizon. These models efficiently distribute the volume of raw materials, increase the capacity utilisation of factories and elevators, and adapt to the current conditions. As a result, the average unloading time decreased by 15%; the cost of hired transport decreased by almost 10%; the total savings on transportation costs per crop amounted to 6.2 mln RUB.

In addition, Rusagro implemented the Russian MES-class production management platform – IndaSoft at its enterprises, including elevators, the oil extraction plant in Balakovo, Saratov region, Russia and the fat plant in Saratov, Russia. It optimises the company's management processes, minimises the risks of disruptions of the production process, and ensures the import substitution.

Finally, Rusagro introduces an integrated approach to the digital transformation of the agro-industrial complex, successfully implementing digital twins to increase efficiency, reduce costs, and ensure sustainable development.

These examples of practical applications of digital twins in agriculture demonstrate their potential in optimising various processes, increasing the efficiency and sustainability of the agro-industrial complex.

Challenges of digital twin implementing

One of the main barriers to the adoption of digital twins is the high cost of their development and implementation. Digital twin function requires the development or purchasing software, stable Internet connection, cloud services for data storage and processing to integrate them into existing enterprise management systems. According to analysts, the cost of implementing a digital twin in agricultural production may exceed 50,000-100,000 USD per medium-sized enterprise, depending on its scale and complexity of the technological infrastructure[3].

The large agricultural holdings, especially in highly competitive conditions, could implement these technologies. However, such investments are unaffordable for small and medium-sized farms, especially in countries with a low level of digitalisation. According to the EU farmers survey, only 27% of small and medium-sized businesses are ready to invest in digital twins in the next 5 years. However, they note insufficient free capital and government support [8].

Additionally, digital twins require investments for start-ups, regular maintenance, software updates, and equipment calibration, increasing overall costs.

Moreover, the effective use of digital twins requires specialists with serious interdisciplinary knowledge in IT, engineering, data management, modelling, and artificial intelligence (AI). Nowadays, there is a serious shortage of such personnel, especially in developing countries [8].

Therefore, farmers and qualified employees of agricultural holdings often have difficulty interpreting the results generated by digital models. It reduces the effectiveness of digital twins using, requiring additional investments in training and retraining of personnel.

The introduction of digital twins often requires significant changes to existing processes and

[3] *Markets and Markets. Digital Twin Market Size, Share & Industry Trends Growth Analysis Report by Application, Industry, Enterprise and Geography – Global Growth Driver and Industry Forecast to 2028. Source: https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html (accessed on 12.03.2025)*

infrastructure. It is difficult and costly, especially for businesses using the outdated technologies. Nevertheless, the integration of digital twins with other systems such as IoT and Big Data requires careful configuration and testing.

The effectiveness of digital doubles directly depends on the quality and volume of data, including sensors, satellite images, and weather forecasts. Insufficient data accuracy or lack cause the incorrect forecasts and decisions negatively affecting the management of agricultural processes.

The main issue is the heterogeneity of data from different sensors and devices. As a result, digital twins might have difficulties in integrating data from various sources, decreasing the accuracy of models and forecasts. Therefore, they require constant monitoring and calibration of equipment.

The quality of data can be directly affected by physical factors, such as failure of certain sensors, sensor drift, or power failures. Journal of Building Performance Simulation examines the issues of using streaming data in predictive digital twins [13].

Moreover, in agriculture digital twins process big data, confidential information on fields, yields, various business processes, etc. It makes them a potential target for cyber-attacks by intruders and competitors. Therefore, it is very important to ensure reliable data protection and compliance with regulatory requirements.

According to the report by Spain's national institute for Cybersecurity, INCIBE-CERT (Spain), digital twins are the critical vulnerability points as their security breach can lead to serious consequences for the operation of all industrial equipment and the safety of workers.

The study by IEEE highlights constant data synchronisation for physical and virtual environments as the relevant security risk in terms of digital twins. The most typical threats are attacks on data transmission channels, malicious interference in decision-making algorithms, and denial-of-service (DoS) attacks. Therefore, minimising risks requires spending on implementing secure communication protocols, encrypting data, creating role-based access, regularly updating software monitoring, and anomaly monitoring [10].

Hence, cybersecurity is an essential element in the implementation of digital twins. Its ignoring or being negligent can cause economic losses and endanger the sustainability of agricultural production.

Conclusion

According to the research results, digital twins are widely used in various fields of the agro-industrial complex, i.e. precision farming, greenhouse crop production, animal husbandry, logistics, agricultural machinery management, and post-harvest processes. Digital twins' implementation in Jeju Island, South Korea, the Netherlands, China, and Russia show the ability of the technology to increase yields, reduce resource costs, and optimise production processes. These examples show the high potential of digital twins as a key tool for improving the sustainability and efficiency of agriculture in limited resources and climate change.

However, the research revealed a number of serious barriers for the widespread adoption of digital twins. They are the high cost of development and implementation, the lack of qualified personnel capable of working with digital counterparts, necessary data quality and security, etc. It is particularly difficult to adapt the technology for small and medium-sized farms – a significant part of the agricultural sector worldwide.

Therefore, digital twins have sufficient potential to become a key tool for the transition to the agriculture of the future. It will provide more productive, sustainable, and adaptive agriculture. It requires coordinated efforts of the scientific community, business, and the government. However, the prospects justify the investments and risks.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR'S CONTRIBUTIONS

Anastasia V. Osadchaya – conceptualization; supervision.
Alexander P. Berus – writing – original draft.

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Improvement of the cost control system based on quality management audit of military-industrial complex enterprises performing state defence order

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ORIGINAL ARTICLE

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Abstract. The article is devoted to the improvement of the cost control system at enterprises of the Defence Industrial Complex (DIC) performing the State Defence Order (SDO). The relevance of the study is determined by the growing requirements for transparency, efficiency, and rational use of financial resources within the framework of public procurement in the defence sector. Traditional cost control systems, based mainly on accounting and self-inspection methods, do not fully meet modern needs, as they fail to ensure a sufficient level of responsiveness to risks, deviations, and inefficiencies in contract execution. The paper proposes a new conceptual and methodological approach that integrates accounting, budgetary, and financial control into a unified system oriented toward compliance with legislation, reliability of financial information, and efficiency of resource allocation. Special attention is paid to the classification of costs incurred in SDO execution, their eligibility for inclusion in fixed contract prices, and their verification in accordance with legal and contractual requirements. The developed methodology introduces intermediate checks of actual expenditures, comparative analysis with planned indicators, and the use of adapted earned value methods for forecasting and decision-making. Practical application of the approach increases the accuracy of price formation, reduces unaccepted costs, and enhances financial sustainability. The results contribute to improving management efficiency and competitiveness of defence enterprises in fulfilling state contracts.

Keywords: State Defence Order; cost control system; separate accounting; price formation; audit of military-industrial complex

JEL codes: M41, H57, L64

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Introduction

Traditional cost control systems used quality control auditing of enterprise management [1]. Based on cost control systems, accounting and control include separate accounting for contracts SDO, and state regulatory methods [3, 4]. At the same time, audits included the self-inspection methods [2]. However, the concepts of audit and self-inspection do not show the price formation in terms of the cost-effective methods. Moreover, increasing the efficiency of enterprises economic activities in terms of SDO performing concerns with the theoretical and methodological base for cost control process. We introduce new approaches to the cost control system and propose new methods for assessment of cost control system effectiveness.

The research suggests the author's definition of the concept of costs and highlights the difference from the concepts of expenses and costs. The following concept based on the difference of the cost requirements set for pricing SDO contracts. Moreover, the classification has been supplemented with the statement: "The costs incurred in the execution of SDO are the company's resources used in their execution. These costs are subject to verification for compliance with the norms of legislation for SDO[1] and the terms of the contract to consider

[1] *On the State Defence Order: Federal Law No. 278-FZ on December 29, 2012 (as amended on 22.04.2024); Decree of the Government of the Russian Federation No. 1465 on 02.12.2017 (as amended on 12.08.2023) "On State Regulation of Prices for Products Supplied under the State Defence Order, and on Amendments and Invalidation of Certain Acts of the Government of the Russian Federation" (with the "Provision on State Regulation of Prices for Products Supplied under the State Defence Order"); Order of the Ministry*

their complying to a fixed price." The paper also considers the factors of influence and industry-specific features of cost control at enterprises of the military-industrial complex in the execution of SDO. These factors determine the prospects for further research of cost control systems, development of their scientifically based methodology in terms of the specifics of defence industry enterprises. Moreover, they construct mathematical models providing data analysis and interpretation and form approaches to determine the effectiveness of these systems and models.

Main part

Indeed, the clarification of cost control systems conceptual framework, their classification, and efficiency assessment, in terms of the specifics of defence industry enterprises executing SDO provided development of a methodology for controlling costs. This methodology is focused on the operational analysis of incurred costs in terms of their eligibility for inclusion in the fixed price under the SDO, development of management decisions aimed at reducing costs. Additionally, it substantiates a mechanism for forecasting the results of financial and economic activities based on the cost control methodology applied during the execution of the SDO, distinguished by the combined use of an adapted earned value method and production.

The developed methodology based on a systematic approach and contains the author's classification and the purpose of control and methods of its implementation. The author's proposal of a three-pronged cost control system allows defence industry to perform public procurement to increase management efficiency (Figure 1).

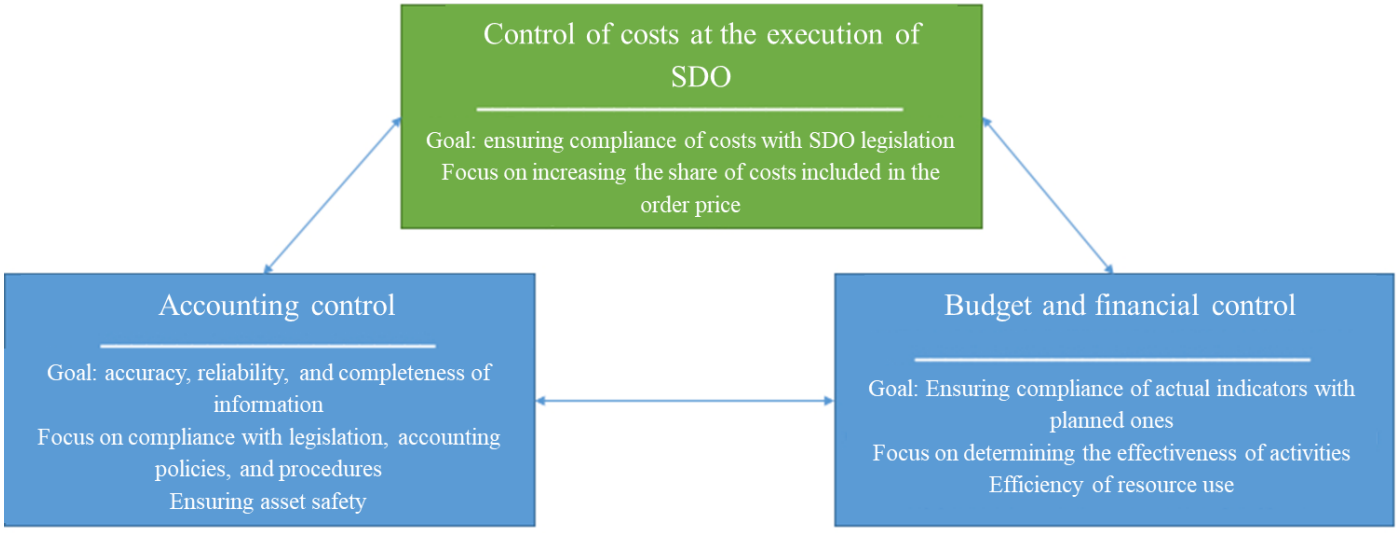

Figure 1. The general scheme of the tripartite cost control system

Source: Author

The Methodology for intermediate checking of costs during the execution of SDO (Figure 2).

The practical significance of our proposals includes more precise accountant activity to make decisions on the reflection of estimated values[2]. For instance, to charge a reserve for the impairment of inventories (work in progress). The constant assessment of contract costs in terms of determining a fixed price provides a reliably estimation of the real fair value of assets such as the cost of work-in-progress orders. It also allows ones to charge an impairment reserve to more reliably reflect the financial condition of the enterprise.

of Industry and Trade of the Russian Federation on February 8, 2019 No. 334 "On Approval of the Procedure for Determining the Composition of Costs Included in the Price of Products Dupplied under the State Defence Order"

[2] *On Accounting: Federal Law No. 402-FZ of December 03, 2011 (amended 12.12.2023)*

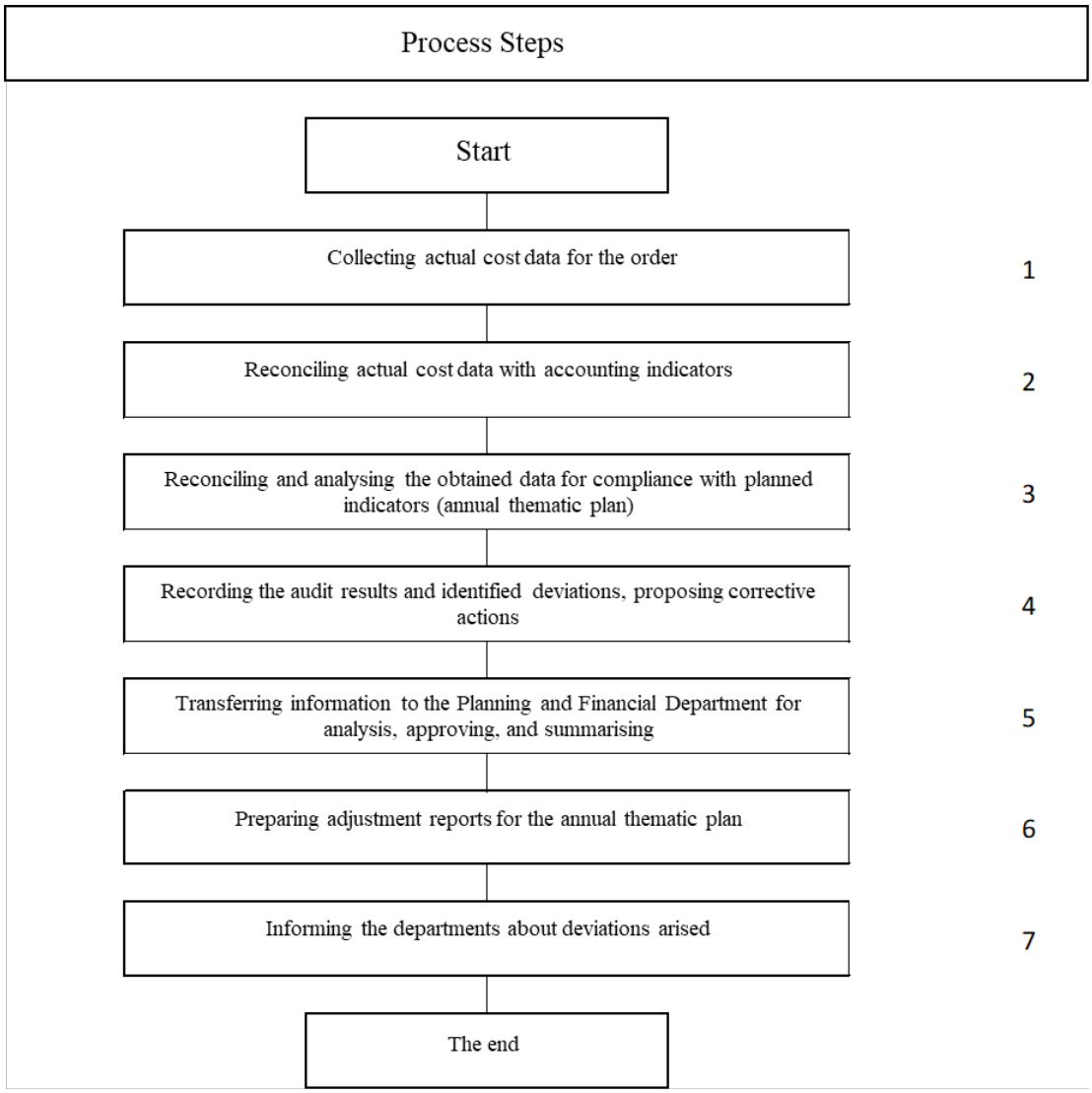

Figure 2. The methodology for intermediate checking of costs during the execution of SDO
Source: Author

The author's cost classification scheme is shown in Figure 3.

Figure 3. Classification of costs for intermediate checking of costs during the execution of SDO
Source: Author

Table 1 shows the indicators (based on [8]) for calculating the adapted mechanism of the production function.

Table 1 – Indicators for calculating the adapted mechanism of the production function. Developed by the author on the basis of the production function model by G.B. Kleiner [9] and earned value method[3]

Indicator	Name	Source	Value
Planned Value	(PV)	Planned Budget Data	Planned Value of Work Done at the Date
Earned Value	(EV)	Planned Budget Data	Planned Cost of Actual Work Done at the Date
Actual Cost	(AC)	Accounting Data	Actual Costs at the Date
Budget at Completion	(BC)	Planned Budget Data	Total Planned Budget
Current Cost Deviation	(CCD)	CCD = EV - AC	A negative value indicates resource overruns.
Cost Performance Index	(CPI)	CPI = EV /AC	A value of more than 1 indicates high efficiency; a value of less than 1 indicates low efficiency.
Forecast at Completion	(FAC)	FAC = BC / CPI	Cost forecast without eliminating of the current deviations
Forecast to Completion	(FTC)	FTC = FAC-AC	Forecast of the remaining costs considering continuing trend towards deviations
Rejection Upon Completion	(RUC)	RUC = BC - FAC	The predicted value of the deviation of actual costs from the planned ones

Source: Author

To determine the current cost of an order, it necessary to:

Based on the data on actual expenditures, and pursuant to the conducted analysis and classification of costs, determine the proportion of costs accounted for in the pricing of products within the framework of the SDO for each item of the cost estimate i:

$$\%CC_i = CC_i / AC_i,$$

where CC_i is the cost of the calculation item in terms of the purpose of SDO pricing; AC_i is the actual cost of the calculation item.

Therefore, the current (as well as the planned, forecast) cost of the order is equal to:

$$C = AC_1 * \%CC_1 * CP_1 + AC_2 * \%CC_2 * CP_2 + ... + AC_i * \%CC_i * CP_i ,$$

where CP_i is the coefficient of profitability according to the calculation method agreed with the customer.

We developed a methodology to determine the effectiveness of measures taken within the framework of the cost control system methodology.

Since the proposed cost control measures are the intermediate stages in the preparation of calculation and costing materials and do not require additional expenses, reporting calculations, price approval, the effectiveness of the control system shall be understood as the coefficient:

$$Ce = (CAC / ACA) \rightarrow 1,$$

where CAC is the cost agreed upon by the customer when forming a fixed price, ACA is the actual cost according to accounting data.

Conclusion

[3] *Minkevich, A. What is the earned value method? Source: https://ampm.by/blog/earned-value-management (accessed on 10.05.2025).*

The efficiency of applying the methodology for intermediate cost control incurred during the execution of SDO has been calculated (see Figure 4).

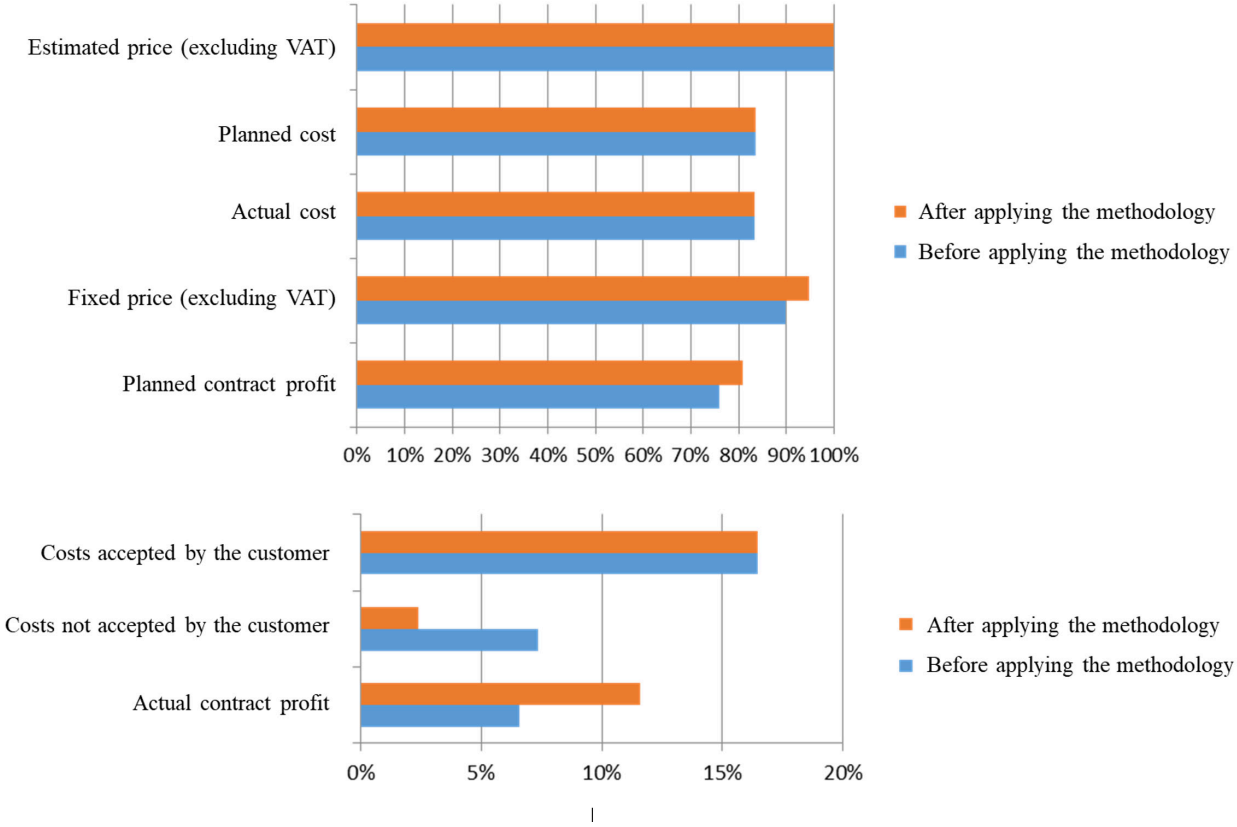

Figure 4. The effectiveness of the Methodology for intermediate checking of costs during the execution of SDO

Source: Author

Ce = 76% / 83% = 0.91 (before applying)
Ce = 81% / 83% = 0.97 (after applying)

As a result, we determine the methods of practical application of author's models for not only SDO industries.

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Company risk-opportunity analysis in conditions of high volatility

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ORIGINAL ARTICLE

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Abstract. The article examines modern theoretical and applied approaches to Risk-Opportunity Analysis (ROA) in the context of unprecedented volatility of the external economic environment. We propose an innovative economic and mathematical model based on a deep integration of scenario analysis methods and fuzzy theory. It ensures an accurate and comprehensive assessment of risk dynamics. The model facilitates the quantitative assessment of various risk – financial, operational, strategic, and reputational ones. It also identifies the key opportunities in terms of innovative technologies and business model adaptation. Model testing based on sampling data from one of a leading company, 2018-2024. The experimental results demonstrate the high effectiveness and predictive value of model proposed. The research proposes a holistic approach to incorporate both quantitative and qualitative volatility factors, provides realistic and actionable foundation for managerial decision-making. The results obtained show a significant practical potential. Moreover, they ensure companies' strategic resilience, adaptability to changes, proactive future management, and ultimately secure sustainable competitive advantages.

Keywords: volatility of the external environment; company risks and opportunities; quantitative risk assessment; fuzzy sets; economic and mathematical modeling

JEL codes: D81, G32, M21, C63, L21, O32, Q54

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Introduction

The modern business environment has a high degree of uncertainty caused by global economic, political, technological, and environmental changes. Therefore, companies have to adapt to rapidly changing market conditions. It requires an effective risk management and the use of emerging opportunities [1]. The relevance of the topic is due to the growing complexity of the external environment and the need to develop new approaches to Risk-Opportunity Analysis (ROA).

Indeed, increasing complexity and dynamism of the modern business environment requires these challenges effective understanding and management. Many authors have studied the issues of volatility and risk management [15, 16, 18, 25]. In particular, the concepts of organisational sustainability and strategic foresight [15] form an important basis for the development of companies adaptive strategies. Scenario planning methods [16] are the most effective tools for analysing the future in conditions of multidimensional uncertainty. They help to model various development trajectories. The application of fuzzy set theory in a business [17] provides new opportunities for accounting subjective expert assessments and qualitative aspects of risks. It is relevant issue to work with implicit data and fuzzy categories. The special attention is paid to

the overall flexibility of the company, its ability to transform financially [7, 18], operationally [8, 20], and strategically [9, 24]. Moreover, company dynamics [24] is crucial for maintaining its competitiveness. The opportunities and risks of digital transformation [19, 23] provide new horizons for research. However, they increase the companies reputational risks [10, 21]. Innovations [12] are sources of competitive advantages and a key factor for competitiveness [22]. In addition to traditional economic [2] and political factors [3, 25], modern business should take into account environmental aspects [5], sustainable development issues (ESG factors) [26], complex decision-making mechanisms [27], and crisis management [28]. All mentioned above require a systematic approach considering the complexity and interdependence of various factors [29].

The purpose of this article is to propose an economic and mathematical model for analysing the risks and opportunities of a company in conditions of high volatility. The research tasks are as follows:

- to study main factors determining the volatility of the external environment;
- to develop an integrative model for combination quantitative analysis methods (i.e. statistical modeling, regression analysis) with qualitative approaches (i.e. expert assessments, case studies);
- to test the model to evaluate its effectiveness.

Hence, we could assess the role of the model in companies' derision-making. The hypothesis of the research is as follows: ROA model will significantly increase both the accuracy of forecasting and the company's adaptability to changes. Moreover, an integrated approach will provide active leveraging of the opportunities arising in uncertain conditions.

Main part

The market volatility is the variability and uncertainty of factors directly affecting the company's activities. It concerns with an economic fluctuations, inflation, crises, market dynamics, changes in demand and competition, etc. Moreover, it is affected on by new regulations, technological advances, innovations, social trends and values, etc. Rapid and unpredictable changing resulted in serious challenges for businesses. Therefore, companies have to constantly adapt to maintain their competitive advantages. Therefore, understanding of volatility could provide a company and business sustainable development. Managing this volatility is crucial for companies to effectively navigate the complexities of the market and make strategic decisions.

The object of the research is a large retailer of consumer goods in several regions of the Russian Federation. The company actively develops its online service and has a diversified product portfolio. The company activities include complex logistics chains and import. Therefore, the company is sensitive to currency fluctuations and different channels interaction with consumers. Those provide operational, reputational, and strategic risks. However, it expands company market share and opportunities in terms of digitalisation, big data analytics, etc.

To respect trade secrets and confidentiality, we cannot provide a company name, as the disclosure of data analysis can damage its competitive position, provide valuable information to competitors, and negatively affect its market strategy. Moreover, depersonalised and aggregated initial data presented in the article show the dynamics and features of business in a highly volatile environment. Therefore, we can demonstrate the effectiveness of the proposed model based without disclosing information. It ensures the practical relevance of the research.

The major factors of economic uncertainty are as follows:

1. Economic (currency fluctuations, inflation, shift in demand) [2].

For instance, during the COVID-19 pandemic, many companies had significant slump in demand for their goods and services.

2. Political (legislative changes, sanctions, political instability) [3].

For instance, the sanctions against Russia in 2022 resulted in the significant changes in international trade.

3. Technological (new technologies, cyber threats) [4, 14].

For instance, the development of AI makes both new opportunities and risks for the companies.

4. Environmental (climatic changes, natural disasters) [5].

For instance, hurricanes and floods are affecting supply chains.

5. Social (changes in consumer preferences, demographic shifts) [6].

For instance, the aging of the population in developed countries establishes new markets for medical services.

The risks of a modern company. Those (financial instability, data leaks, or reputational crises, etc.), arise at the intersection of rapidly changing technologies and a dynamic market. As a result, companies should have flexible and innovative management. Nowadays, companies should anticipate possible threats and turn them into opportunities for growth and development.

The risks of the company are classified as follows:

1. Financial risks caused by instability in the capital markets [7]. The currency fluctuations could cause significant financial losses for corporations operating in the international market.

2. Operational risks arising from disruptions in production and logistics [8]. For instance, global supply chain disruptions were triggered by the COVID-19 pandemic.

3. Strategic risks associated with miscalculations in the development of long-term development plans [9]. For instance, the companies do not provide their own digital transformation have lost their competitiveness.

4. Reputational risks associated with negative public perception of the company [10]. For instance, the leakage of confidential data damages brand credibility.

The modern economic situation provides unique opportunities for companies' innovative development and growth. The companies flexibility and adaptability to changing market conditions allow them to withstand challenges and gain strategic advantages from them. Therefore, instability could resulted in creativity increasing, innovative solutions, and development of the new products. Additionally, it establishes new forms of cooperation and strategic partnerships, resulted in strengthening of companies market positions. Therefore, successful companies often became leaders, defining new development vectors.

In the context of economic volatility companies could have the following benefits:

1. To adapt business models to new realities [11]. For instance, the shift of companies to remote work during the pandemic.

2. To use innovations as a source of competitive advantages [12]. For instance, the introduction of blockchain technologies could increase the transparency and security of operations.

3. To implement advanced technologies for risks reducing [13]. In particular, AI helps to forecast demand, optimise logistics, and avoid the excess inventory.

To analyse risks and opportunities, we have proposed an economic and mathematical model based on the integration of scenario analysis and fuzzy set theory. The model includes the following steps.

1. Identification of risks and opportunities (using SWOT and PEST analysis).

2. Quantitative assessment (based on fuzzy set theory; the risks and opportunities are described by a membership function).

3. Scenario modelling (development of scenarios for the company's development in terms of different levels of volatility).

Hence, the model is as follows (1):

$$R = \sum_{i=1}^{n} w_i \cdot \mu_i(x), \tag{1}$$

where R is the integral risk assessment;

w_i is the weight of the i-th risk factor;

$\mu_i(x)$ is a i-th factor membership function to a fuzzy set.

The results of the proposed model implementation are shown in Table 1. According to the analysis of the experimental data, there is a strong dynamics in the ratio of risks and opportunities of the company, 2018-2024. However, the results should be considered in details.

Table 1 – Implementation results

Year	Risk 1 (currency fluctuations)	Risk 2 (supply disruptions)	Risk 3 (errors forecasting)	Risk 4 (negative customers reviews)	Opportunity 1 (online platform)	Opportunity 2 (expansion of the assortment)	Opportunity 3 (big data)	Opportunity 4 (local suppliers)	Integral risk	Integral opportunity	Sustainability
2018	0.72	0.65	0.50	0.40	0.89	0.78	0.85	0.75	0.68	0.83	0.75
2019	0.71	0.64	0.49	0.39	0.88	0.77	0.84	0.74	0.67	0.82	0.74
2020	0.73	0.66	0.51	0.41	0.90	0.79	0.86	0.76	0.69	0.84	0.76
2021	0.74	0.67	0.52	0.42	0.91	0.80	0.87	0.77	0.70	0.85	0.77
2022	0.75	0.68	0.53	0.43	0.92	0.81	0.88	0.78	0.71	0.86	0.78
2023	0.76	0.69	0.54	0.44	0.93	0.82	0.89	0.79	0.72	0.87	0.79
2024	0.77	0.70	0.55	0.45	0.94	0.83	0.90	0.80	0.73	0.88	0.80

Source: Authors

1. Risk dynamics

Risk 1 (currency fluctuations). There is a steady trend towards an increase; its quantitative assessment increased from 0.72 in 2018 to 0.77 in 2024. These dynamics is a reflection of the growing instability in global currency markets caused by a series of economic crises and the transformation of the monetary policy of key states [2]. Therefore, to mitigate potential losses, companies are actively applying strategies for hedging currency risks and other financial tools.

Risk 2 (supply disruptions). The risk index shows significant growth, from 0.65 in 2018 to 0.70 in 2024. The main drivers of this negative dynamics are the increasing global disruptions, such as the COVID-19 pandemic, the aggravation of geopolitical tensions, and the climatic agenda [5]. Therefore, it is necessary to diversify the supplier pool and implement advanced real-time supply chain monitoring systems.

Risk 3 (errors forecasting). The indicator has increased from 0.50 to 0.55. The reason is the increasing unpredictability of consumer behaviour in the conditions of macroeconomic volatility [6]. To improve the accuracy of forecasts, it is necessary to integrate modern big data processing methods and AI models into the company's analytics.

Risk 4 (negative customer reviews). The risk showed an increase from 0.40 to 0.45. This trend directly correlates with the growing influence of social media and online platforms on companies reputation [10]. To effectively manage this risk, it is critically important to implement a comprehensive monitoring system for the digital landscape, providing mechanisms for rapid response to negative information.

Opportunity 1 (online platform). The significance of this opportunity has been demonstrated by a steady increase from 0.89 in 2018 to 0.94 in 2024. The observed growth correlates with the global trend of increasing popularity of e-commerce and a marked shift in consumer preferences to remote purchases [12]. Moreover, the company took advantage of the prevailing market conditions and successfully implemented relevant initiatives. It is directly reflected in the increase in the share of online sales in total revenue.

Opportunity 2 (expansion of the assortment). The impact of the product range expansion strategy has also increased, from 0.78 in 2018 to 0.83 in 2024. It shows the effectiveness of the ongoing product diversification strategy, attracted new customer segments and increased the average purchase price [6]. Additionally, it had a positive impact on business sustainability and reduced its dependence on seasonal fluctuations in demand.

Opportunity 3 (big data). The use of big data to ensure company efficiency increased from 0.85 to 0.90. The growth is provided by the successful implementation of advanced analytical tools. It leads to more accurate demand forecasting and optimisation of inventory [13]. Moreover, it resulted in increase of customer satisfaction and a reduction in transaction costs.

Opportunity 4 (local suppliers). The importance of this strategy increased from 0.75 to 0.80. It is a result of a focused strategy to localise supply chains. Consequently, it minimises the risks associated with global disruptions in logistics chains, strengthen company reputation, reduces logistics costs, and improve brand perception [11].

3. Integral indicators

Integral risk. There is a growth in integral risk; its value increased from 0.68 in 2018 to 0.73 in 2024. The data obtained show make increasing instability of the external environment. It requires active and proactive risk management strategies implementation. According to the analysis, the key factors (drivers) caused the growth of this indicator are increased volatility in the foreign exchange markets and permanent disruptions in global supply chains.

An integral opportunity. The value of the integrated opportunity shows positive dynamics, having increased from 0.83 to 0.88. Indeed, it is a result of the successful implementation of strategic initiatives, online platform, and big data into the market analysis and customer interaction. The increase in the integrated opportunuty indicator indicates the increased ability of the company to adapt and effectively respond to changes in the volatility.

The sustainability of the company. The calculated consolidated indicator of the company's sustainability showed an increase from 0.75 to 0.80. The presented results empirically confirm both the adequacy and effectiveness of the assessment model proposed, the overall success of the company's strategic course aimed at integrated risk management and capitalising on emerging opportunities. Moreover, the steady growth of this indicator is also an indicator of strengthening the company's competitive position in the market.

Conclusions

Therefore, the scientific novelty of the conducted research is in the development of a comprehensive model integrated quantitative and qualitative methods of ROA. Moreover, the model proposed considers financial, operational, strategic, and reputational risks, as well as opportunities associated with innovation and the use of new technologies. Indeed, the practical significance of the research helps to improve the accuracy of forecasting risks and opportunities, develop strategies aimed at reducing risks and exploiting opportunities.

Hence, traditional risk analysis methods mentioned in the literature [1, 2] concerns mostly to the financial aspects and quantitative metrics. It reduces their effectiveness for assessing difficult-to-predict qualitative risks and rapidly changing opportunities. Many approaches [7] focus on the retrospective analysis or on highly specialised risks, such as market or credit risks and ignore the relationship between their multiplicative impact in conditions of uncertainty. The model proposed integrates scenario analysis [16] and fuzzy set theory [17]. Scenario modelling proactively considers various future options, including extreme events. It significantly exceeds static or extrapolation forecasts. The use of fuzzy sets is critically important for assessing risks and opportunities (i.e. reputational [10, 21], strategic [9, 24], or innovative [12, 22]). Those are difficult to accurately quantifying and require expert subjective assessment. It allows the model proposed to be more flexible and adaptive to complex and poorly structured problems than systems based on statistical data only. This approach considers a wide range of factors and meets modern requirements for strategic planning in conditions of increased volatility [15, 29].

The results obtained are presented in Table 1. Those provide convincing confirmation of these advantages. The observed steady increase in integral risk from 2018 to 2024 (from 0.68 to 0.73), in particular due to currency fluctuations and disruptions in supply chains, clearly shows the ability of the model proposed to accurately capture and quantify the increasing volatility. Indeed, it shows the limitations of traditional models. At the same time, the growth of the integrated opportunity (from 0.83 to 0.88) shows our model effectively identifies and measures the development potential arising from the introduction of online platforms [12] and big data [13]. It agrees with modern concepts; according to them, opportunities are the result of purposeful strategy and flexibility of the company [11, 22]. The most significant is the growth of the company's sustainability index from 0.75 to 0.80. It confirms the adequacy of the model proposed. Moreover, it is critically important in terms

of the scientific literature on business sustainability [15, 24]. The integrated approach actively manages both risks and opportunities. It leads to a real strengthening of the company's competitive position and increased adaptability – a key goal in volatile economics. Therefore, the model proposed concerns with diagnostic and analytical tools to analyse companies current state, form future strategies, etc.

However, the research has its limitations.

1 The model proposed was tested on data from a single company. It definitely limits conclusions extrapolating.

2 The model does not consider relevant ESG criteria.

3 Nevertheless, improving the accuracy of risk assessment and potential opportunities requires data analysis over a longer time horizon.

Promising areas for further research are as follows: first, there is an urgent need to expand the model by integrating ESG indicators as an integral part of the sustainable development strategy. Secondly, it is critically important to test the developed approach on representative samples from various sectors of the economy to verify its universality. Thirdly, the adaptation of artificial intelligence (AI) and machine learning methods (MLM) to improve the accuracy of predictive calculations has a significant potential. Moreover, to investigate the impact of global trends such as digital transformation and decarbonisation on the sustainability of business models is an urgent task. Additionally, it is necessary to study the following phenomena: a corporate culture and an analysis of the complex cause-and-effect relationships between risk appetite and innovation activity of companies in the risk management system; the transformation of risk perception in the context of global shocks; the analysis of business strategies adaptation to the regulatory requirements; development of a methodological framework for assessing the long-term consequences of management decisions in conditions of profound uncertainty. Their implementation will significantly improve theoretical knowledge and expand risk management tools.

Hence, a proposed model provides the advanced development of risk and opportunity analysis methodology. Its practical application ensures companies stability and strengthens their competitive positions in the global market. The results obtained confirm a significance of effective risk management and timely implementation for sustainable business development. Therefore, for many companies the developed model is an effective strategic planning tool to adapt to future changes. The versatility of its approach allows its adaptation in various industries. It makes the model a valuable asset for both large corporations and small and medium-sized businesses. However, its successful implementation requires the organisational changes, including investments in staff training and the formation of cross-functional working groups.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR'S CONTRIBUTIONS

Aleksandr V. Borovkov – conceptualization; supervision.
Igor P. Uvarov – writing – original draft.
Boris I. Storchun – data curation.

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Modern company management based on AI: a holistic and forecasting approaches

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ORIGINAL ARTICLE

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Abstract. The article examines the challenges of managing a modern company in increasing dynamics of digital transformation. Moreover, the integration of artificial intelligence (AI) is a key element ensuring company management flexibility, adaptability, and proactivity. The development of a holistic hierarchical economic-mathematical model synthesises strategic planning, operational management, and predictive analytics. The model is based on machine and deep learning algorithms, and considers dynamic interrelationships between internal and external factors influencing the company's activities. The research considers practical aspects of AI implementation in critical business processes, analyses its on companies key performance indicators, 2020-2024. It also studies industry specifics, macro- and microeconomic trends, and socio-cultural aspects. The implementation of AI intensifies decision-making, minimises cognitive biases, optimises time costs, affects the operational processes, increases both the level of customer interaction personalisation and the company's competitiveness. Moreover, the article concerns with AI ethical aspects, development of control and regulatory mechanisms to provide transparency, fairness, and responsible decision-making.

Keywords: digital transformation; artificial intelligence; economic and mathematical modeling; holistic approach; prognostic approach

JEL codes: M15, O33, C63, L86, M21, D81

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Introduction

The modern economic situation is fundamental transformation of the structure of markets, the evolution of consumer preferences, a change in the paradigm of interaction between market participants, and an acceleration of technological progress. In the dynamic environment the concept of digital transformation dominates. It is a fundamental reconfiguration of the company's business models based on the deep integration of digital technologies into all aspects of its activities from strategic planning to operational management [1, 2].

Recently, various approaches to digital transformation have been actively discussed in the scientific literature. There are a lot of researches concerning AI. According to the papers [16-20], AI successful implementation requires technological readiness, corporate culture changes, staff retraining, and revision of business processes. For instance, the study [16] analyses the impact of AI on strategic management; [17] examines the risks associated with labour automation. The authors of [18] propose a model for assessing the digital maturity of companies; [19] studies the role of AI in the formation of competitive advantages. The works [20, 21] consider the ethical aspects of AI, issues of algorithms transparency and responsibility for decisions based on machine learning; [22] discusses methods for integrating AI into value chains; [23] analyses the impact of digital technologies on sustainable business development; [24, 25] focuses on companies adaptation to new technologies; [26] analyses the role of AI in risk management; [27, 28] consider the influence of AI on marketing strategies; [29] explores the role of digital platforms in the transformation of business models; [30] examines the prospects for the development of AI in the conditions of global economic challenges.

Indeed, AI is the key driver of this transformation. It is able to automate routine operational tasks, intelligently analyse vast amounts of data, model future trends, and make informed management decisions in uncertain and dynamically changing business environment. However, the effective implementation of AI requires the expensive software, transformation of the companies structure, the development of digital

culture, and staff retraining to work effectively with new technologies. Therefore, an integrated approach should consider both technological and organisational aspects of AI implementation [3, 6]. This approach absence could result in failure of the expected returns and have negative impact on the company's activities.

Hence, the relevance of the research is provided by the necessity of a systematic analysis of AI impact on company management and the development of practical tools for its effective implementation. Moreover, our research offers a holistic model combining strategic, operational, and analytical dimensions of AI-based management. It allows us to overcome the fragmentation of approaches typical for many modern studies [16, 20, 24].

In this regard, there is an urgent need to develop fundamentally new approaches to managing a modern company. They should be based on the integration of AI at all levels of decision-making and consider the relationship between various factors affecting companies effectiveness. The purpose of the research is to develop and validate a holistic hierarchical economic and mathematical model of company management. The model includes AI-based digital transformation, assessment of AI impact on key performance indicators. The model also considers industry specifics, macro- and microeconomic trends, and socio-cultural aspects.

According the hypothesis of the research, developed holistic management model based on the integration of AI increases the efficiency of a company by optimising business processes, improving the quality of decisions making, increasing the personalisation of customer interaction and adaptability to changing market conditions.

The scientific novelty of the research is as follows:

1. The development of a holistic hierarchical economic and mathematical model to integrate strategic planning, operational management, and forecasting analytics based on AI. The mosel should consider various factors affecting the company's activities.

2. The methodologies for assessing the digital maturity of a company to determine companies' readiness to implement AI and develop an individual digital transformation strategy.

3. The tools for monitoring and assessment AI impact on companies' key performance indicators in terms of the industry specifics and macroeconomic factors.

4. An approach to company management based on ethical principles and ensuring transparency, fairness, and responsibility in decision-making.

Methods

An interdisciplinary approach was used as the methodological basis of the research. It combines the methods of system and cognitive modelling analysis, mathematical and simulation modelling, statistical and big data analysis, and expert assessments. We develop a holistic hierarchical economic and mathematical model to integrate strategic planning, operational management, and AI-based analytics.

Model Description

The proposed holistic hierarchical management model based on the integration of AI is a multi-level adaptive system. It ensures consistency of goals and objectives at each management level in terms of the relationship between internal and external factors affecting company activities.

1. Strategic Level (macro level). At this level, a company establishes long-term development strategy, defines the strategic goals and objectives, analyses the external environment (macroeconomic factors, industry trends, technological changes, socio-cultural aspects), assesses risks and opportunities, allocates resources, etc. AI analyses big data (market, competitor, consumer data, and technology trends), forecasts demand, models company development scenarios, optimises investment decisions, develops marketing strategies, and assesses a company performance. Moreover, key performance indicators (KPIs) are formed. They are used to assess the effectiveness of the company itself and its individual divisions. The relevant aspect is the assessment of a company digital maturity to determine companies' readiness to implement AI and develop an individual digital transformation strategy.

2. Operational Level (meso-level). At this level, the operational management of business processes, control over the implementation of plans and coordination of departments activities are provided. AI automates

routine operational tasks (robotic process automation – RPA), optimises logistics and inventory management (demand forecasting, optimisation of delivery routes, inventory management), manages production processes (forecasting analytics, optimisation of equipment schedules, product quality control). It also controls the marketing campaigns (personalisation of advertising, targeting, effectiveness of advertising campaigns), customer service management (chatbots, automatic customer request analysis systems, personalisation of service), human resource management (personnel search and selection, employee performance assessment, identification of training and development needs), etc.

3. Analytical Level (microlevel). At this level, data on the company's activities is collected, processed, and analysed; patterns and anomalies are identified, risks and opportunities are forecasted, data-driven decision making is supported, the effectiveness of the company and its individual divisions is controlled. AI analyses big data (sales, customer, production process, logistics, financial and transaction data), identifies patterns and trends, forecasts risks and opportunities, and develops recommendations for improving business processes and the company's performance. The analytical level provides feedback between the strategic and operational levels of management to correct the plans and strategies in accordance with changing market conditions and the company's performance. An important element of the analytical level is the use of cognitive modelling methods to analyse consumer behaviour and making effective marketing decisions.

The scientific novelty of the model is in the development of a holistic approach to company management based on the integration of AI at all levels of management in terms of the relationship between various factors affecting the company's performance; using advanced machine and deep learning methods to analyse big data and forecast future trends; considering industry specifics, macro- and microeconomic trends, and socio-cultural aspects in development of a digital transformation strategy; development a system for monitoring and assessing the company's performance based on KPIs; quickly respond to changes in market conditions and adjust plans and strategies; development of an approach to company management based on ethical principles; ensuring transparency, fairness, and responsibility in decision-making; integration of cognitive modelling techniques to analyse consumer behaviour and make effective marketing decisions.

Mathematical description of the model:

1. Strategic planning function (F_S) (1).

$$F_S = argmax\ \{ E[U(X,Y,Z,W,V)|\Theta] - \lambda R(I,\sigma,\rho), \quad (1)$$

where U is a utility function depending on performance indicators: X (revenue growth in terms of both market share and dynamics), Y (cost reduction in terms of the cost of AI implementing and the cost of capital), Z (increased customer satisfaction in terms of loyalty and personalisation), W (social responsibility and ESG factors in terms of environmental, social, and managerial aspects of sustainable development), V (innovation, design and development of new products and services);

R is a risk function depending on investments in AI (I), the level of uncertainty in the external environment (σ), and the level of company digital maturity (p);

λ is the coefficient of risk aversion determined by the company's risk profile, strategic goals, and the level of digital maturity;

Θ – information on the state of the external environment obtained using AI methods (big data analysis, machine learning, deep learning, natural language processing, machine vision);

E [...|Θ] is the mathematical expectation of the utility function provided information about the external environment. The U function could be a a weighted sum of performance indicators in terms of the company's strategic priorities.

2. Operational Control function (F_O) (2)

$$F_O = min\ \{ C(A,B,Q,S) + \mu P(E,\delta,\varepsilon)\}, \quad (2)$$

where C is a cost function depending on the level of automation (A), resource efficiency (B), management quality (Q), and speed of adaptation to environmental changes (S);

P is a loss function depending on targets deviations (E), the level of uncertainty in the operating environment (δ), and ethical risks associated with the use of AI (ε);

μ is the coefficient of loss significance; it shows the company's priorities regarding compliance with targets, risk minimisation, and ethical standards;

A is the level of process automation determined by the proportion of automated tasks and the use of AI to optimise operations (robotic process automation, machine vision, natural language processing);

B – resource efficiency calculated as the ratio of results to resources expended (material, financial, labour, energy, environment) in terms of sustainable development;

Q – quality management on the basis of expert assessments and indicators of management processes effectiveness (speed of decision-making, level of coordination, effectiveness of communications, level of motivation of employees);

S is the rate of adaptation to changes in the external environment; it is assessed through the rate of new technologies introduction, change in business processes, and the speed of response to changing customer needs.

3. AI-based analytics function (F_A) (3)

$$F_A=argmin\ \{(1/N)\Sigma[y_i-f(x_i,\theta,\omega,\xi)]^2+\gamma\Omega(\theta)+\eta\Psi(\omega)+\zeta\Xi(\xi)\} \quad (3)$$

where y_i is the actual value of the indicators;

f (x_i, θ, ω, ξ) are forecasting values obtained using ensemble machine learning algorithms and cognitive modelling (the function f depends on the input data x_i, model parameters θ, the weights of the assambly ω, and the parameters of the cognitive model ξ);

Ω(θ) is a regularisation function to prevent overfitting of machine learning models;

Ψ(ω) is a regularisation function providing balance between different models in assembly;

Ξ(ξ) is a regularisation function ensuring the adequacy of the cognitive model and preventing its overfitting based on historical data;

γ is the regularisation coefficient for machine learning models;

n is the regularisation coefficient for the weights of the assembly;

ζ is the regularisation coefficient for the parameters of the cognitive model;

N is the number of observations.

Model Practical Testing

To verify the effectiveness of the pilot testing of a holistic hierarchical management model in the real economy, we conducted a retrospective analysis of the operational data of an anonymous company. Those develops IT tools for medium and large businesses, 2020-2024. To respect trade secrets and confidentiality, we cannot provide a company name, as the disclosure of data analysis can damage its competitive position, provide valuable information to competitors, and negatively affect its market strategy. Nevertheless, company provided data analysed in an aggregated form; it confirms data scientific value.

The research considers the industry specifics, determinants of macro- and microeconomic conditions, and socio-cultural factors.

Initially, we selected this company from 100 typical companies on the innovation market. The company designs and develops IT tools for medium and large businesses. The main selection criteria were as follows: assessment of experience and stability in the market (the minimum period of work in the market is at least 5-10 years); financial stability and positive dynamics of key indicators (revenue, profit); reputation and customer reviews (reliability rating, partner certificates); specialisation (focus on IT-solutions and digital transformation, work with medium and large enterprises, availability of innovative products and services related to AI and automation); business size and scale (number of employees providing integrated processes, geographical coverage, and customer base sufficient to summarise research results); availability and quality of data (availability of data collection systems, data storage and analysis (BI, CRM, ERP systems), the company's willingness to cooperate and provide data for research. compliance with confidentiality and ethics requirements); digital maturity and innovation potential (availability of a digital transformation strategy, the use of AI and modern technologies in business processes, the level of investment in R&D and innovation); willingness to provide data for analysis with respecting all confidentiality requirements. Indeed, this approach

to data anonymisation is widely used in academic research for commercial information [21, 26].

The following performance indicators were considered: revenue growth index (in terms of market share and dynamics); cost reduction index (in terms of the cost of implementing AI and the cost of capital); customer satisfaction index (in terms of loyalty and personalisation); business process automation index (in terms of the complexity of tasks and the level of qualification of personnel); resource efficiency index (in terms of environmental factors and principles of sustainable development); the innovation activity index (in terms of the number of new products and services launched on the market and investments in R&D) [4].

The company under study has been operating in the market for more than 15 years. It has a reputation as a reliable partner offering innovative and effective tools for business process automation, data management, cybersecurity, and digital marketing. The company's digital maturity at the beginning of the study period (2020) was assessed as average one. However, that time it did not use AI, machine learning, and big data. However, the management of the company under study was aware of the need for digital transformation, the expediency of investing in new technologies, and staff training.

Results

The results of the implementation of the AI model are shown in a retrospective analysis (Table 1).

Table 1 – Dynamics of performance indicators of the company under study in AI-based digital transformation

Indicator	2020	2021	2022	2023	2024
Revenue Growth Index	1.05	1.08	1.12	1.18	1.25
Cost Reduction index	0.98	0.95	0.92	0.88	0.83
Customer Satisfaction Index	1.02	1.04	1.07	1.11	1.16
Business Process Automation Index	0.35	0.48	0.62	0.77	0.92
Resource Efficiency Index	1.01	1.03	1.06	1.09	1.13
AI and Revenue Correlation Coefficient	0.00	0.25	0.52	0.78	0.95
AI and Costs Correlation Coefficient	0.00	-0.28	-0.55	-0.81	-0.97
Share of Automated Tasks	0.20	0.35	0.50	0.65	0.80
Demand Forecasting Index	0.85	0.90	0.95	1.00	1.05
Logistics Optimisation Index	0.90	0.93	0.96	0.99	1.02
Operational Risk Reduction Index	0.95	0.92	0.89	0.86	0.83
Marketing Effectiveness Index	1.03	1.06	1.09	1.12	1.15
Innovation Activity Index	0.97	1.01	1.05	1.10	1.16
Digital Maturity Index	0.40	0.55	0.70	0.85	0.95
AI Ethical Responsibility Index	0.75	0.80	0.85	0.90	0.95

Source: Author

According to data analysis, targeted implementation of AI within the framework of a holistic hierarchical management model has a significant positive impact on key company performance indicators. However, the effectiveness of AI implementation depends on the level of digital maturity of the company, industry specifics, macro- and microeconomic trends, and socio-cultural aspects. The revenue growth index increased by 19%, 2020-2024. It shows an increase in the company's competitiveness and market share. The revenue growth was achieved through the introduction of AI into marketing, sales, and customer service processes. It personalises offers, improves customer service, and increases customer loyalty. The cost reduction index decreased by 15%. It shows the optimisation of operational processes by automating routine tasks, increases resource efficiency, and reduces inventory management and logistics costs. The introduction of AI into production processes increases productivity, reduces waste, and optimises the use of energy resources. The customer satisfaction index increased by 14%. It shows an improvement in the quality of products and services, an increase in the

level of personalisation of service, and prompt response to customer requests. The introduction of chatbots and automatic analysis systems for customer requests has significantly improved the quality of customer service and increased their loyalty.

The growth of the business process automation index is particularly relevant as it increased by 57%, 2020-2024. This is due to the introduction of AI into various areas of the company's activities, including manufacturing, logistics, marketing, customer service, and human resource management. The resource efficiency index also shows positive dynamics. It indicates the optimisation of the use of material, financial, labour, energy, and environmental resources. The company actively implements the principles of sustainable development and uses AI to monitor and manage environmental risks. The innovation activity index increased by 16%. It shows an increase in the number of new products and services introduced to the market and the efficiency of investments in R&D.

The positive dynamics of these indicators is supported by a significant increase in the correlation coefficients between the introduction of AI and changes in revenue (an increase to 0.95) and costs (a decrease to -0.97). It shows a strong causal relationship between these factors. Increasing the share of automated tasks (up to 80% by 2024) has reduced operational risks, improved demand forecasting accuracy, and optimised business processes. However, the introduction of AI into marketing activities has increased their effectiveness by 12% (an increase in the marketing effectiveness index from 1.03 to 1.15). It shows an increased return on investment in marketing and brand awareness. An increase both in the company's digital maturity level (an increase in the digital maturity index from 0.40 to 0.95) and ain the level of ethical responsibility when using AI (an increase in the AI ethical responsibility index from 0.75 to 0.95) is relevant factor of the model effectiveness.

Generally, the company under study demonstrates a gradual steady systematic growth of the integrated AI-based performance indicator as part of the implementation of a holistic hierarchical management model from 1.01 in 2020 to 1.19 in 2024. Indeed, an annual increase is 3-5%. Figure 1 shows this trend in the form of an ascending chart, emphasising the steady positive dynamics without significant fluctuations.

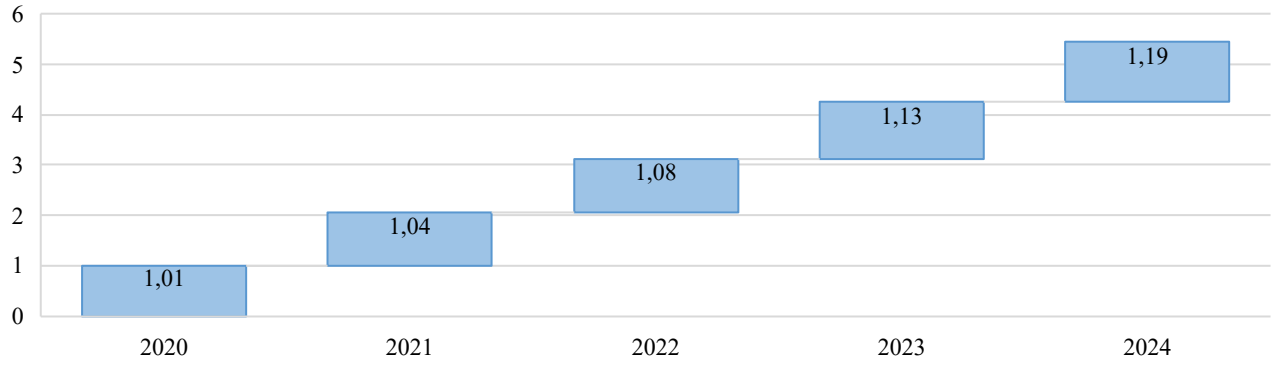

Figure 1. Dynamics of AI based integrated efficiency indicator

Source: Author

In general, the data show an increase in the effectiveness of AI technologies during the study period. It might indicate progress in their implementation and optimisation.

Conclusions

The results obtained confirm the main hypothesis of the study concerning with AI significant positive impact on the effectiveness of company management in the context of digital transformation. The developed holistic hierarchical economic and mathematical model integrates strategic planning, operational management, and AI-based analytics. It provides an integrated approach to management and increases its effectiveness. However, the effectiveness of AI implementation depends on many factors, including the level of digital maturity of a company, industry specifics, macro- and microeconomic trends, and socio-cultural aspects [6].

The results are consistent with the results of other studies [3, 5, 9, 12, 13]. AI introduction can optimise costs, improve the quality of products and services, increase productivity, the level of personalisation of services, and adaptability to changing market conditions. However, AI introduction requires significant investments in technology, infrastructure, staff training, and business process changes [6]. Moreover, advanced development of AI ethical aspects, its control and regulatory mechanisms ensure transparency, fairness, and responsibility in decision-making [7, 8, 15].

The major contribution of this research is the development of a holistic company management model based on the integration of AI. It considers the relationship between various factors affecting the company's performance and ensures its adaptability, flexibility, and proactivity. The model helps to manage resources more efficiently, optimise business processes, improve the quality of decision-making, increase the level of personalisation of customer interaction and company competitiveness.

AI is a key factor in improving the management efficiency of a modern company in digital transformation. The developed holistic hierarchical economic and mathematical model integrates strategic planning, operational management, and AI-based analytics. It provides an integrated approach to management and increases its effectiveness. The results of the retrospective analysis confirm the positive impact of AI on the key performance indicators of the company. However, the effectiveness of AI introduction depends on the level of company digital maturity, industry specifics, macro- and microeconomic trends, and socio-cultural aspects.

Nevertheless, the research limitations should be taken into account when interpreting the results. Firstly, the analysis was based on a single company data. It limits generalising the conclusions to other industries and business models. Secondly, the retrospective analysis does not correspond to assessment of AI implementation in a rapidly changing technological environment. Thirdly, some socio-cultural and ethical aspects of AI require additional qualitative research. Finally, the limited time horizon (2020-2024) does not consider possible structural changes in the economy affecting the effectiveness of AI in the future. These limitations ensure the prospects for further research, including cross-industry comparative analyses, the development of dynamic models of companies' adaptation to technological innovations, etc. [24, 29, 30].

The research results can be used to develop a digital transformation strategy, introduce AI into business processes, assess the effectiveness of investments in AI, and develop ethical principles. Further research might study complex management models in terms of the specifics of various industries and companies, or development the methods for assessing and managing risks associated with the use of AI. [9, 10, 11, 14]. Therefore, it is necessary to develop tools for staff training and AI professional development, protect against discrimination and bias in AI based decision-making.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

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