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WYDAWNICTWO POLITECHNIKI ŚLĄSKIEJ
ul. Akademicka 5, 44-100 Gliwice
tel. (32) 237-13-81, faks (32) 237-15-02
www.wydawnictwopolitechniki.pl

Sprzedaż i Marketing
tel. (32) 237-18-48
wydawnictwo_mark@polsl.pl

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FOREWORD

Presented number of Silesian University of Technology. Scientific Papers. Organization and Management Series. Presented papers contain result of researches conducted by various universities. The number consists of 33 papers.

The papers presented in the number concentrate on many topics connected with organization and management. There are in the number papers about: artificial intelligence implementation in management; environmental management; marketing; industry management; public management; innovation management; finances; sustainability; smart city; entrepreneurship; human resource management; safety management; quality management; economics; e-business and business models.

Radosław Wolniak

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ARTIFICIAL INTELLIGENCE AND THE DEVELOPMENT OF BUSINESS MODELS IN THE GAMING INDUSTRY – CASE STUDY

Beata BARCZAK[1]*, Kamila KWIATKOWSKA[2]

[1] University of Economics in Krakow; barczakb@uek.krakow.pl, ORCID: 0000-0003-0345-2267
[2] University of Economics in Krakow; kwiatkok@uek.krakow.pl, ORCID: 0000-0002-4007-179X
* Correspondence author

Purpose: This article examines the impact of artificial intelligence (AI) on the evolution of business models in the video game industry. The main objective is to fill the research gap concerning how AI integration not only generates new business models but also modifies existing ones, influencing companies' strategies and players' experiences. The study addresses the tension between innovation and risk, showing how AI adoption reshapes value creation, delivery, and capture within this creative sector.
Design/methodology/approach: The research combines a systematic literature review (SLR) of 56 Scopus-indexed publications with qualitative empirical analysis. A comparative case study approach was adopted, focusing on Ubisoft, which actively experiments with generative AI, and CD Projekt, which deliberately limits AI use. The criteria of analysis included strategic goals, the degree of creative control retained by developers, and the legal and ethical challenges of AI-driven innovation.
Findings: The results reveal that AI enables cost optimization, higher player retention through personalization, and novel monetization models such as NFTs and dynamic pricing. Ubisoft uses AI tools like Ghostwriter and NEO NPC to automate NPC dialogues and create dynamic interactions, enhancing immersion while maintaining authorial oversight. In contrast, CD Projekt refrains from integrating generative AI into flagship projects like The Witcher 4, citing copyright and quality concerns, and applies AI only in supportive functions such as testing or voice reconstruction. These contrasting strategies show that AI's impact on business models depends on technological choices and risk tolerance.
Research limitations/implications: The study is limited to global trends and two cases; future research should include regional and ethical perspectives.
Practical implications: Game developers can leverage AI to optimize processes and retention, but must apply legal audits and ethical safeguards.
Social implications: AI expands gaming as a social and cultural space but raises concerns about manipulation, copyright, and creativity.
Originality/value: The study integrates theory and practice, showing how contrasting AI strategies transform business models and offering a framework for future industry adoption.
Keywords: business models, artificial intelligence, video game industry.
Category of the paper: Research paper.

1. Introduction

Artificial intelligence (AI) is becoming increasingly important in various sectors, including the rapidly evolving video game and computer gaming industries. AI offers a wide range of innovation opportunities, from enhancing the behavior of non-player characters (NPCs) to procedural content generation and personalization of gameplay (Filipović, 2023). Thanks to its transformational potential, artificial intelligence is beginning to penetrate various sectors of the economy, and the video game industry is no exception. It is a sector of enormous and constantly growing global importance (Filipović, 2023).

It is worth emphasizing that globally, the number of players in 2021 was approximately 2.9 billion, representing a significant increase from 2015. In such a dynamic and competitive environment, business models are a key element of the strategy for companies operating in the gaming industry, determining how to create, deliver, and capture value. Despite the growing role of AI in various aspects of video game creation and operation, including enhancing visual experiences, optimizing gameplay, and creating more realistic environments, research on its impact on the evolution of business models in this industry is fragmented. Most existing work focuses on the technical aspects of AI implementation in games, such as the behavior of non-playable characters (NPCs), procedural generation of worlds, or the implications of personalizing player experiences. However, there is a lack of comprehensive analyses that systematically examine how AI integration contributes to the emergence of new business models, modifications to existing ones, and what implications this has for businesses and consumers.

Despite AI's rapid growth in the video game industry, comprehensive analyses of its impact on business model (BM) evolution remain scarce. Existing research focuses on technical aspects (e.g., NPC behavior), overlooking systemic transformations in value creation, delivery, and capture. Crucially, it is unclear how polarized AI adoption strategies - from experimental (Ubisoft) to cautious (CD Projekt) - reshape BMs and generate implications for innovation, creative control, and legal/ethical risks.

Based on the research problem formulated in this way, the following research questions were defined:

1. How does generative AI integration reconfigure core BM elements (production, experience personalization, monetization) in gaming?
2. What factors (technological, legal, cultural) determine firms' AI strategies and their impact on innovation?
3. To what extent does the tension between AI-driven innovation and legal/ethical risks necessitate BM redefinition?

This article aims to fill this gap by adopting a theoretical and empirical approach. Therefore, this article seeks to investigate the impact of AI on the evolution of business models in the gaming industry. The following detailed objectives operationalized this objective:

1. Conceptualization of the concept of business model in the context of the gaming industry.
2. Description of the specificity of the gaming industry, taking into account its key trends and characteristics.
3. Review of business models currently operating in the gaming industry.
4. Analysis of the impact of AI on the gaming industry business models – a case study of two selected companies from the gaming industry.
5. Indication of directions for further research.

This study actively engages with two pivotal scholarly controversies: (1) technological determinism vs. strategic choice in business model transformation (Teece, 2010), and (2) the "creativity vs. automation" dilemma in cultural industries (Dhar, 2015). Challenging deterministic narratives about the inevitability of full automation in creative sectors (e.g., Koch, 2016), our findings demonstrate that AI adoption is a contingent process, shaped by organizational context and risk tolerance. The polarization of Ubisoft's (experimental) and CD Projekt's (cautious) strategies refutes claims of a universal innovation pattern, instead affirming the role of firm agency in steering technological trajectories (Jabłoński, 2013). Moreover, by identifying "creative control guardrails" as a response to generative AI risks, the article contributes to AI ethics debates (IEEE, 2023), the concept of hybrid autonomy, where algorithms augment, but do not replace, human creative intuition. The originality of the study stems from combining a systematic literature review with a qualitative analysis of contrasting AI implementation case studies, offering a novel theoretical framework and practical implications for the creative sector.

2. Theoretical Background

2.1. The Gaming Industry Context

The modern gaming industry, one of the most dynamically developing sectors of the digital economy, has undergone profound transformations in the last decade in terms of technology and business. A breakthrough in the development of this industry and the history of games occurred in 1972, when Pong, often considered the first video game, was released to the market. In the same year Atari was founded, the first console was introduced, and the first video game arcade opened, marking a rapid period of industry development over a short span (Massé, Paris, 2022). The convergence of these events does not have to be accidental, as it was generally at this time that the content, distribution channels, and the company, in the form of Atari, were formed, which were to play a fundamental role in the developing industry. Unlike the film industry, which developed gradually over many decades, the video games sector reached a similar level much faster, which is evidence of its exceptional dynamics.

Like any industry, the video game sector requires effective strategies to gain market advantage and meet player expectations. Success depends on attracting top talent and innovative business models, but strategy must vary regionally, adapting to cultural, technological, and consumer preferences (like casual players or MMORPG fans). Game type (e.g., FPS, RPG) and monetization (premium, freemium, F2P, subscription) are crucial, alongside constant hardware innovation (Klimas, 2017).

The gaming industry, one of the most dynamically developing creative industries, is part of the creative sector. Creative sector companies are characterized by producing products of high symbolic, intellectual, and cultural value (Kasprzak, 2013). Several key features distinguish the products of the creative industry. First, their creation requires a significant contribution of human creativity, which gives them a unique character. Secondly, they convey a symbolic message that extends beyond basic functionality, offering recipients additional emotional, intellectual, or aesthetic value. Thirdly, they contain potential intellectual property that can be attributed to a specific person or group of creators (Kroeber, Kluckhohn, 1952).

In the gaming industry context, the entire range of benefits that both their representatives and the whole economy derive from the achievements of creative sectors (spillover effect) should be considered. The spillover effect in the creative sector (also applicable to the gaming industry) is a process in which innovations, knowledge, and benefits developed in one industry or company permeate other sectors or companies, generating additional profits for them.

Referring to the concept of the entrepreneurial ecosystem (Isenberg, 2011), the development of business models (and value propositions) in the gaming industry is not the result of a specific action of one person or the effect of a single idea, but the result of a shared vision of a group of stakeholders creating appropriate conditions for the development of enterprises. Creative industries from different sectors can inspire each other to develop their creativity, even if, at first glance, these industries appear unrelated.

Video games are an extremely complex and interdisciplinary medium. They are a dynamic combination of art, narrative, music, and technology. This synthesis allows for the creation of interactive experiences that are a permanent part of contemporary culture's landscape, constantly evolving at the intersection of creativity and innovation. A good example of this transformation is the interpenetration of games with other forms of entertainment, as evidenced by virtual concerts and events organized in games such as Fortnite. Performances by artists such as Travis Scott, Ariana Grande, and Eminem contribute to strengthening the role of video games as multidimensional entertainment platforms with a global reach (Forbes, 2024).

2.2. SLR Methodology

The systematic literature review (SLR) methodology was employed, which not only allows for a formalized and objective synthesis of previous scientific achievements or an assessment of previous research (Gimenez, Tachizawa, 2012), but also enables the identification of both researched and unexplored areas (Levy, Ellis, 2006).

The process of systematic literature review, which is the basis for the search and analysis of existing types of business models in the gaming industry, was carried out in three stages (Anello, Fleiss, 1995), starting from the creation of a literature database (phase I), through the selection of works finally included in the database (phase II), and ending with a critical content analysis (phase III). This process was based on appropriately selected keywords and a methodology adapted to the specificity of the researched area. The entire process, including the SLR stages, is detailed in Table 1.

Table 1.
Summary of the results for the search string

Stage	Description	Phrases/Keywords	Number of results
Initial Search	Scopus search	(gaming OR game) AND (industry OR sector) AND business AND (model OR models)	1432
Abstract Analysis	Identification of key terms	business model/models, subscription/s, game/gaming/games, freemium, free-to-play, microtransactions, peer-to-peer	--
Pre-selection	Exclusion of irrelevant publications	--	583
Detailed analysis	Focus on business models in the gaming industry	free-to-play, freemium	128
Final selection	Removal of duplicate, inaccessible or low-quality texts	--	56

Source: Authors own work.

The primary tool used in the search was the Scopus database, where the search phrases "gaming OR game" AND "industry OR sector" AND "business" AND "model OR models" were employed. The initial search results yielded 1,432 publications created between 2002 and 2025. The first step in the selection process was the analysis of abstracts, which aimed to identify works containing key terms related to the area of research interest. The keywords included in this analysis were, among others, business models, subscription, game, gaming, freemium, free-to-play, microtransactions, and peer-to-peer. Additionally, important phrases were identified that could potentially expand the results in subsequent stages. In the next stage, exclusion criteria were applied, limiting the set of publications to those relevant to the research topic. Texts that did not contain the indicated keywords that were inappropriate to the discussed topic or referred to the analyzed issue in a different context than the one adopted in the study were excluded. This process reduced the number of potential sources to 583 publications, which were then subjected to a more detailed evaluation.

The focus was on content related to business models specific to the video game industry, such as free-to-play and freemium, as well as other popular solutions used in this sector. After a thorough review of the publications' content, texts unrelated to the topic were removed, reducing the number of analyzed works to 128. Duplicates, unavailable texts, and those of insufficient quality were eliminated, resulting in a database of 56 publications. This process allowed us to create a coherent and comprehensive body of literature analyzing business models specific to the video game sector. The literature review was also conducted using the "snowball"

method – that is, to further extend the literature review by locating and examining additional scientific sources not included in the selected database (Zhang, Banerji, 2017). The use of the ResearchRabbit tool supported the application of this method. Additionally, the research results were based on the analysis of key industry reports (e.g. whitepapers) and company case studies.

2.3. Research results

After analyzing the content of the articles, a conceptual framework for a business model was developed, situating it within the context of the gaming industry. Then, an attempt was made to indicate the types of business models in the gaming industry.

2.3.1. Business model concept

A business model is a complex and multifaceted issue that has been the subject of numerous scientific analyses for years. The variety of its definitions reflects the broad range of interpretations and practical applications of this concept. Among the earliest approaches to this problem is the proposal by Magretta (2002), who views a business model as an idea of how a company can generate income. A similar approach was presented by Koźmiński (2004), who defines a business model as an idea for making money, focusing on its function as the foundation of economic activity. Obłój (2002) expanded this perspective, indicating that a business model is not only a plan for generating income but, above all, a combination of a strategic concept with the technology of its implementation. According to this approach, a business model enables effective use of the company's resources and competencies. At the same time, it is subject to the risk of rapid imitation by competitors. Subsequent definitions introduced new elements to the understanding of this term (Shafer et al., 2005). highlighted key components of a business model, including strategic choices, value creation and capture, and the value network, thereby emphasizing its complex nature as a management tool.

More contemporary approaches emphasize adapting the business model to meet the needs of the market and its users. Teece (2010) underlines in his definition that a business model should be user-oriented, difficult to imitate, and consistent with market realities, which allows the company to achieve a sustainable competitive advantage. In turn, Jabłoński (2013) emphasizes the combination of tangible assets and intellectual capital as the basis for implementing a value growth strategy. According to him, the business model's attractiveness and flexibility enable the company to adapt dynamically to a changing environment, thereby increasing its market value.

A business model, The Business Model Canvas is a tool for visualizing and designing business models. Its creator is Alexander Osterwalder, who developed this concept as part of his doctoral thesis and subsequently, together with Yves Pigneur, popularized it in the book "Business Model Generation" (Osterwalder, Pigneur, 2010). Thanks to its structure, the Business Model Canvas allows entrepreneurs and managers to present, test, and modify a business model quickly and transparently. The Business Model Canvas plays a crucial role in

facilitating effective communication within teams and supporting strategic decision-making. Its structure allows for flexible responses to market changes characterized by high dynamics, forcing organizations to constantly adapt and implement innovations in their business models (Osterwalder et al., 2012). As a result, this tool has gained widespread popularity in strategic management and business planning; an example of its application is provided in Table 2.

Table 2.
Business Model Canvas for Fortnite games

<table>
<tr>
<td rowspan="2">Key partners
- Gaming platforms (e.g., PlayStation, Xbox, PC, mobile).
- Content creators and streamers (e.g., YouTube, Twitch).
- Collaborations with franchises (e.g., Marvel, Star Wars).
- Advertisers and sponsors.</td>
<td>Key Actions
- Game development and updates.
- Hosting in-game events and collaborations.
- Managing in-game shop and Battle Pass system.
- Community engagement through social media and forums.</td>
<td rowspan="2">Proposal values
- Free-to-play gaming experience.
- Immersive battle royale gameplay with building mechanics.
- Customization through cosmetic items (skins, emotes).
- Regular updates and special events to keep players engaged.</td>
<td>Relationships with clients
- Community-driven engagement (forums, social media).</td>
<td rowspan="2">Segments customers
- Casual gamers.
- Competitive players (eSports).
- Content creators and streamers.</td>
</tr>
<tr>
<td>Key resources
- Epic Games' development team and Unreal Engine technology.
- IT infrastructure for online gameplay.
- Intellectual property (game modes, characters, skins).</td>
<td>Channels
- Digital platforms: PC, Mac, PlayStation, Xbox, Nintendo Switch, iOS, Android.
- Social media platforms: YouTube, Twitch, Discord.
- In-game shop.</td>
</tr>
<tr>
<td colspan="2">Structure costs
- Game design and development costs.
- IT infrastructure maintenance.
- Marketing and promotional campaigns.
- Employee salaries</td>
<td colspan="3">Streams revenues
- In-app purchases via V-Bucks (cosmetic items like skins and emotes).
- Seasonal Battle Pass subscriptions.
- Premium game mode (Fortnite: Save the World).
- Partnerships and advertising revenue.</td>
</tr>
</table>

Source: Authors own work.

The Business Model Canvas for the free-to-play game Fortnite illustrates how various elements attract and retain players, as well as generate revenue. Significant partnerships with gaming platforms, content creators, franchises, and advertisers play a crucial role in expanding the game's reach and appeal to a broader audience. At the same time, creating and regularly updating the game itself, organizing events, and effectively managing the in-game store are the foundations of user engagement. Free access to the game, extensive personalization options, and frequent updates and events effectively attract new players while retaining existing users. Fortnite appeared on the market relatively soon after the spectacular success of Playerunknown's Battlegrounds (PUBG). Thanks to its free availability on every device, it achieved unprecedented popularity, whereas PUBG only transitioned to a free-to-play model after a few years (Osterwalder, Pigneur, 2010).

2.3.2. Selected Business Models in the Gaming Industry

The video game industry employs various business models that differ in revenue structure and how they engage and retain players. Based on the SLR results, several key models have been identified, which are presented in Table 3.

Table 3.
Selected business models in the gaming industry

Type of business model	Description
Free-to-play	A model based on a free-to-play game that later offers the possibility of numerous microtransactions thanks to long player retention.
Pay-to-play	A model based on a paid game that does not include subsequent financial demands.
Subscription	In addition to the initial price of the game, you must pay a monthly subscription to continue playing.
GaaS (Games as a Service)	The model allows developers to keep the game up to date, releasing as many updates as they want, when they want, allowing all players to receive them immediately upon connecting to a server.
Play-to-earn	NFT-based model that opens a new frontier of secondary markets where all game participants can trade in-game services, features, and items.

Source: own study based on SLR: (Tao, 2012; Liao, 2016; Guintcheva-Sapino, 2017; Jones, 2020; Sinclair, 2017; Tomić, 2019).

The free-to-play model involves providing the basic version of the game for free, with the option to purchase virtual goods or opt out of advertisements. Its development was a response to widespread piracy in China, which slowed the industry's growth even after the country joined the World Trade Organization (WTO) in 2001 (Tao, 2012). The government's lack of action against piracy compelled companies to adopt new methods of monetization, which contributed to the widespread adoption of the free-to-play model (Liao, 2016). Unlike the free-to-play model, the pay-to-play model is based on a one-time fee for full access to the game, with no further financial obligations. This generates a quick profit, but it requires higher production costs. Pay-to-play games offer full content on the day of release, and any additional content is typically available as paid add-ons (DLC). The subscription model, popularized by MMORPGs (e.g., World of Warcraft), combines the purchase of the game with a mandatory regular subscription fee for maintaining access to servers (Jones, 2020).

A breakthrough in the development of business models in the gaming industry is the GaaS (Games as a Service) model, which enables developers to continually update the game, manage relationships with players, segment the audience, and personalize content (Sinclair, 2017; NoBlue, 2018). The primary revenue streams are generated through microtransactions, which enable the purchase of unique items and personalization elements (Tomić, 2019).

The most modern business models in this industry utilize blockchain and NFTs, enabling players to trade virtual goods and generate revenue (Wi, 2009; Popescu, 2021). An example is the game Decentraland, where tokens can be used to buy and sell virtual real estate (Decentraland, 2021). The play-to-earn model combines fun with real economics, redefining digital ownership.

The current macroeconomic situation and slowdown in player growth are prompting PC and console game developers to experiment with new business models, particularly subscription-based and micropayment models. Extending the life cycle of games and developing the game-as-a-service (GaaS) model, as well as creating their distribution ecosystems and building customer loyalty, are the latest trends on the market.

2.3.3. Possibilities of using artificial intelligence in game development

Artificial Intelligence (AI) is increasingly important in the gaming industry, offering tools for creating more complex and immersive experiences. One of the key areas of its application is the development of non-player characters (NPCs) with human-like behavior, which is a challenge due to the need to balance predictability and spontaneity (Uludağlı, Oguz, 2023). This method, which has been used since the 1990s in series such as Battlefield and Tomb Raider, provides stability but is limited to a narrow range of scenarios programmed by the creators (Lou, 2017). In response to the need for greater adaptability, developers are turning to advanced techniques such as the Monte Carlo Tree Search (MCTS) algorithm, which analyzes potential player moves in real-time and dynamically adjusts the NPC's strategy (Cowling et al., 2012). Combining reinforcement learning with neural networks, deep learning has even more potential. This allows NPCs to simulate decisions based on experience, such as avoiding repeated mistakes or predicting player tactics, bringing their behavior closer to human intuition (Koch, 2016; Dhar, 2015). However, AI goes beyond character creation; it also streamlines production processes. Automating game testing, which traditionally required thousands of hours of work, now relies on algorithms that detect logic errors, collisions, or mechanical imbalances. This enables teams to concentrate on the creative aspects of design, thereby reducing development time and costs (Hawk, 2023).

An example is the solution implemented by 2K Games, which used AI to generate unique weapon textures in Borderlands 2, saving artists time (Kuo, 2012). In turn, Ubisoft utilized AI to dynamically balance gameplay and matchmaking in Rainbow Six Siege, adjusting the difficulty to match players' skills (Maguid, Jacquier, 2018). Innovative applications of AI also include the creation of environments. Microsoft used algorithms to generate realistic landscapes in Flight Simulator procedurally based on satellite and meteorological data. Similar techniques can be adapted to build open worlds where AI designs complex ecosystems or manages interactions between characters. In the future, integrating AI with technologies such as blockchain or NFT may enable the creation of games where virtual worlds evolve organically and NPC decisions affect the game economy or relationships between players. However, it is already clear today that AI optimizes production and redefines the boundaries of interactivity, making games more alive and unpredictable.

3. Empirical Studies

3.1. Research Methods

The empirical research used qualitative methods, particularly the case study method and comparative analysis.

As Yin (2018) noted, a case study is a research method that focuses on an in-depth understanding of a single case or several cases in their natural context. It is beneficial in researching complex phenomena whose boundaries are not clearly defined, which perfectly corresponds to the characteristics of the dynamically developing gaming industry and the implementation of AI solutions in it. This study employs the approach proposed by Yin (2003, 2018), which comprises three main stages: defining and designing the study, preparing for data collection, and collecting and analyzing the data. In defining and designing the study, two cases were selected - Ubisoft and CD Projekt - as representative examples of different AI implementation strategies in the gaming industry. The criteria for selecting cases included: (1) scale of operations (large development studios), (2) different approaches to AI implementation, and (3) data availability. As Yin (2018) emphasized, the appropriate selection of cases is crucial to ensuring the study's validity.

The case study method has several important features. The holistic approach enabled the analysis of the AI implementation phenomenon within each company's organizational, cultural, and technological context. The method's flexibility allowed for the modification of the research process in response to new information emerging during the analysis. The information was obtained by collecting information from various sources, including secondary data (annual reports, press releases) (Ubisoft, 2024; Online Games, 2025).

The comparative analysis of both cases was conducted according to defined criteria, including (1) strategic goals in the use of AI, (2) approach to generative AI, (3) impact on business models, and (4) challenges and constraints. Two extreme cases were compared here. As case studies indicate, while Ubisoft is actively implementing generative AI solutions (Ghostwriter, NEO NPC) to optimize creative processes (Ubisoft, 2024), CD Projekt is taking a more cautious stance, focusing on traditional content creation methods and limited use of AI for supporting purposes (Gry Online, 2025).

3.2. Case study

3.2.1. Ubisoft

Ubisoft, a leader in the video game industry, is actively exploring the potential of artificial intelligence (AI) in the design and production processes of games. As part of this strategy, the company is implementing two key projects: the Ghostwriter tool and the NEO NPC prototype, both of which were developed through the cooperation of the R&D teams at Ubisoft La Forge and Ubisoft Paris Studio. Ghostwriter, a tool developed by Ben Swanson,

R&D specialist at La Forge Montreal, aims to streamline the work of video game scriptwriters. Swanson explains that Ghostwriter automates the time-consuming process of creating "shoulders" - short NPC statements triggered by specific events in the game, such as crowd conversations or reactions during combat (Ubisoft, 2024). Working with the tool is based on human cooperation with AI technology. First, the scriptwriters define the character profile and the nature of the interaction, and the Ghostwriter generates different variants of the statement. Then, the creators select and edit the best proposals, ensuring consistency with the game's narrative.

The algorithm learns from these decisions, thereby improving the quality of the generated content. Swanson emphasizes that "Ghostwriter allows writers to spend more time developing the core narrative, rather than focusing on rough drafts of dialogue" (Ubisoft, 2024). The NEO NPC project, developed by the Ubisoft Paris Studio team, explores the possibilities of generative AI in creating NPCs capable of engaging in dynamic and spontaneous conversations with players. Collaborations with Nvidia, Audio2Face, and Inworld enabled the team to develop AI language models (LLMs) that expand the boundaries of player-character interactions while maintaining their authenticity (Ubisoft, 2024).

A key part of the project is shaping the AI model so that its statements stay true to the narrative. Mélanie Lopez Malet, data scientist, explains, "We always ask ourselves, 'Would Lisa say this?' If the answer is no, we analyze the model and adjust to return to Virginie's vision" (Ubisoft, 2024). Malet adds that the iterative process allows the model to reflect the creators' intentions better while eliminating biases or stereotypes. Ubisoft places particular emphasis on maintaining the authenticity of the characters and control over their narrative roles. Mosser emphasizes, "These characters have no will of their own. They are part of the story and have a narrative purpose" (Ubisoft, 2024). To ensure consistency, the team uses a system of "guardrails" - firewalls that control NPC behaviors, protect against toxic player interactions, and keep the character within their intended character arc. Malet explains, "Inappropriate player impulses are filtered through a model that adjusts NPC responses while maintaining the narrative tone" (Ubisoft, 2024). Despite the new possibilities it opens up, implementing AI into game design has many challenges to overcome. Swanson notes that integrating Ghostwriter into production processes requires both technical support and adapting the tool to the specific realities of the project (Ubisoft, 2024). Mosser and Malet, on the other hand, point to the need to eliminate linguistic biases and balance creative freedom with narrative requirements (Ubisoft, 2024). Ubisoft sees the potential of its AI technologies in both large AAA productions and smaller projects. Guillemette Picard, Senior Vice President of Production Technology, emphasizes that generative AI is only valuable when it supports human creativity. "Our goal is to develop technology that amplifies the creative visions of creators and benefits players", Picard summarizes (Ubisoft, 2024).

3.2.2. CD Projekt

CD Projekt, a Polish developer known for titles such as The Witcher series and Cyberpunk 2077, approaches the issue of using artificial intelligence (AI) cautiously and rationally. While other studios, such as Ubisoft, are experimenting with generative AI, CD Projekt focuses on research and development of tools supporting the creative process. However, it does not include generative AI technologies in its key projects, such as The Witcher 4. As Adam Badowski, co-president of CD Projekt, points out, AI is considered in the context of supporting production processes, but "creative" AI (generative AI) raises many problems, including copyright-related risks. Badowski, during the summary of the company's financial results for fiscal year 2024, emphasized that "generative AI is quite troublesome when it comes to the issue of legal ownership of brands and many other aspects" (Gry Online, 2025). For this reason, CD Projekt does not plan to implement such technologies in The Witcher 4 or other currently developed projects until key legal and technical issues are resolved. For the same reason, as Michał Nowakowski, another co-president of the company, notes, CD Projekt is in no hurry to implement AI in the narrative elements of its games. The company prefers a traditional approach to writing dialogues and character design, leaving complete creative control in the hands of scriptwriters (Gry Online, 2025).

However, the company conducts research on AI in other areas. As revealed in the annual report for 2024, Redsi is developing several research projects related to AI, focusing on aspects such as:

- Test automation - using AI to detect bugs in games.
- Realistic NPC crowds - AI models support the creation of more natural crowd behaviors.
- Prototyping process - AI tools help in rapid testing and iteration of design ideas.

Despite this research, the company focuses on moderate implementation of AI in practical applications. As the report suggests, CD Projekt's AI team is exploring the possibility of creating algorithms and models explicitly tailored to the studio's needs, rather than using ready-made generative AI solutions (Inwestycje.pl, 2025).

An interesting example of CD Projekt's use of AI was the reconstruction of the voice of the deceased actor Miłogost Reczek in the Phantom Liberty add-on for Cyberpunk 2077. The team worked with the voice engineering company Respeecher to recreate the actor's voice with the consent of his family. As Mikołaj Szwed, localization director at CD Projekt, explains, "it was a way to pay tribute to his extraordinary talent" (Gry Online, 2023). The process involved using another actor to record new lines of dialogue, which were then transformed into Miłogost Reczek's voice using AI technology, with the approval of the actor's family.

CD Projekt's use of AI remains limited compared to the more experimental approaches of other companies. This decision stems from concerns about the quality and consistency of the generated content, as well as ethical and legal issues. Problems such as potential copyright infringement or quality limitations of generative models lead the company to avoid implementing these technologies on a broader scale. However, this does not mean that

CD Projekt will completely exclude AI in the future. As indicated by Inwestycje.pl (2025), the company monitors the development of the technology. Once the technical and legal issues are resolved, it does not rule out its broader use in its projects.

Table 4 presents a comparison of the AI strategies of Ubisoft and CD Projekt.

Table 4.
Comparison of AI strategies between Ubisoft and CD Projekt

Criterion	Ubisoft	CD Projekt
Main goals of the strategy	Scaling creative processes, improving immersion through dynamic NPC interactions, and automating dialogue generation.	Limited AI research in improving prototyping, test automation, and realistic NPC crowds.
Approach to AI	Hybrid – AI supports writers while maintaining their creative control (Ghostwriter and NEO NPC).	Caution – AI is not being used in a generative form in current projects due to legal and ethical concerns.
Application of generative AI	Experimental – Ghostwriter generates rough drafts of dialogues; NEO NPC creates dynamic conversations with NPCs.	Limited – Use of AI in a generative form only in the reconstruction of the deceased actor's voice in Cyberpunk 2077.
Creative control	Creators decide on the final shape of AI-generated content.	Complete creator control – AI does not replace or support writers in the narrative processes of current projects.
Scale of application	Dynamic AI development in various areas, from narrative to AAA game prototyping and smaller projects.	Initial AI research – implementation in production processes limited to selected experiments.
Market Impact	Setting new standards in the use of AI in game narrative, an inspiration for other developers.	A cautious stance towards AI, emphasizing the importance of ethics and content quality, does not significantly impact the AI innovation market.
Challenges	Integrating AI into production processes, controlling biases of language models, and educating teams in AI tools.	Issues related to copyright and the ethical use of AI, as well as a lack of practical solutions for generative AI.
Impact on technology	Developing generative AI for narrative, iteratively improving language models, and creating new tools for creators.	AI research in pre-production, test automation, and realistic NPC movement (without the use of generative AI models).

Source: own study based on: Ubisoft (2024), Gry Online (2025), Inwestycje.pl (2025), Gry Online (2023).

Ubisoft stands out for its advanced integration of AI into the game development process. Projects such as Ghostwriter and NEO NPC show that generative AI can effectively support creators while maintaining their creative control. The company contributes to developing AI technology in gaming while expanding narrative possibilities through more immersive interactions with NPCs. On the other hand, CD Projekt cautiously approaches AI, focusing on research and analysis of its potential. The company avoids generative AI in current projects, such as *The Witcher 4*, due to concerns about legal, ethical, and content quality issues. The use of AI is limited to niche cases, such as the reconstruction of a deceased actor's voice in *Cyberpunk 2077*. CD Projekt focuses on a traditional approach to narrative, which allows for full creative control while closing the door to more innovative applications of AI in the game.

4. Discussion

The presented considerations show that the differences in both companies' approaches to AI implementation are reflected in their business models. Ubisoft aims to increase production efficiency and shorten development cycles by automating creative processes, critical in service-based models (GaaS). In turn, CD Projekt's strategy, which focuses on maintaining complete control over the creative process, aligns with the premium model, where the key value is the quality and artistic consistency of the production.

The conclusions from the comparative analysis indicate that AI's impact on business models in the gaming industry is complex and depends on the technological strategy adopted. While AI solutions can significantly reduce production costs and increase user engagement, their implementation is associated with legal and ethical challenges, which - as exemplified by CD Projekt - may encourage some companies to adopt a more cautious approach.

The research allows us to conclude that artificial intelligence increasingly impacts business models in the video game industry, transforming production processes and monetization strategies. The Ubisoft case study shows how Ghostwriter and NEO NPC tools can significantly improve game development, especially regarding content generation and interactions with non-player characters (NPCs). As Swanson (2024) notes, automating dialogue creation allows writers to focus on key narrative elements while reducing production time and costs.

In the context of business models, AI's impact on personalizing player experiences is significant. Research indicates that machine learning-based algorithms, used in Roblox's recommendation systems or dynamic gameplay balancing in Rainbow Six Siege, can increase user retention by up to 20-30% compared to traditional solutions (Liu, 2022). This increased retention translates directly into the effectiveness of free-to-play models, where time spent in the game and user engagement are key indicators of success.

At the same time, the development of AI technology creates new monetization opportunities. Virtual economies based on NFTs, such as in Decentraland (2021) or dynamic pricing systems that adapt to player behavior (Kholodylo, Strauss, 2023), are examples of innovative approaches that would be impossible without advanced AI algorithms. Ubisoft is experimenting with NPCs capable of natural conversations, which could create entirely new forms of interaction and related revenue streams.

It is worth noting, however, that the implementation of AI in the gaming industry is not uniform. While Ubisoft is actively investing in generative AI, CD Projekt is approaching this technology with greater caution, focusing on traditional methods of content creation (Gry Online, 2025). This difference in approach stems from both legal concerns about copyright and concern for the quality and artistic integrity of the production.

The ethical challenges associated with the use of AI in games also warrant attention. The problem of algorithmic bias, visible, for example, in attempts to create diverse NPC characters (Ubisoft, 2024), or the issue of excessive personalization that can lead to manipulative monetization mechanics, requires the development of appropriate standards and regulations. Ubisoft utilizes solutions such as "guardrails" in NEO NPC, which are designed to provide control over the generated content. However, as Malet (Ubisoft, 2024) points out, these systems still require improvement.

Despite undeniable benefits in personalization, the use of AI in games raises serious ethical challenges, such as algorithmic manipulation and the phenomenon of "surveillance capitalism." Algorithms analyzing vast sets of player behavioral data can be used not only to recommend content but also to subtly influence their purchasing decisions and time spent in the game. Mechanisms for dynamically adjusting difficulty, intentionally creating frustration (e.g., through constant losing), or displaying personalized microtransaction offers at moments of the player's greatest emotional vulnerability can lead to manipulative monetization practices. In the "surveillance capitalism" model (Zuboff, 2019), the player and their data become the product; their experience is designed to maximize engagement and spending, often at the expense of their autonomy and well-being. This necessitates the development of transparent standards and consent mechanisms (e.g., based on the GDPR model) that will give players absolute control over their data and how it is used to shape the gaming experience.

Excessive personalization, driven by AI algorithms, also carries the risk of adverse side effects. One of the most serious is the potential to deepen game addiction. Algorithms striving to maximize retention can create engagement loops that are extremely difficult to break, leading to problematic usage patterns and harm to mental health. Furthermore, recommendation systems and personalized experience paths can create "filter bubbles" for players, effectively limiting their exposure to diverse play styles and content, which ultimately impoverishes the shared, social experience of the game. Another risk is "overmonetization" – aggressively targeting users prone to spending large sums (so-called "whales"), which can lead to significant financial losses and exploit the vulnerabilities of individuals with impulse control disorders. Therefore, balanced personalization design should consider not only business goals but also an ethical duty of care to protect the user.

In summary, AI is becoming increasingly important in transforming business models in the gaming industry. Its influence is manifested in three main areas: optimizing production processes, increasing user engagement, and creating new monetization opportunities. However, as the example of CD Projekt demonstrates, fully leveraging this potential requires addressing significant legal and ethical challenges. Further development of this technology in the industry will depend on developing a balance between innovation and responsible implementation of solutions based on AI.

Based on the presented considerations, the following practice recommendations were formulated:

Following Ubisoft's example, creators should implement control systems (e.g., content filtering, creative oversight) for generative AI to protect artistic integrity and avoid legal risks.

- Creating hybrid innovation models - it is advisable to combine AI with human processes, for example, automating testing (CD Projekt) or generating initial dialogue versions (Ubisoft), while preserving creators' decision-making power.
- Auditing legal risks - before using generative AI in projects (e.g., asset generation), an audit of copyright and training data should be conducted to avoid disputes (recommendation for studios like CD Projekt).
- Ethical Personalization - algorithms analyzing player data (e.g., for microtransactions) must be transparent and avoid manipulation; implement IEEE standards (2023). Pilots in low-risk projects - generative AI should be tested in smaller productions or DLCs (e.g. voice reconstruction in Cyberpunk 2077), not in key IPs.

5. Directions for Future Research and Conclusion

Future research on the impact of AI on gaming business models should focus on overcoming current technological, legal, and ethical barriers while exploring new opportunities for integrating AI with emerging technologies.

First, a key direction is to analyze the legal challenges associated with generative AI, particularly in the context of intellectual property rights for content created by algorithms. As the example of CD Projekt demonstrates, ambiguities regarding copyrights to AI-generated dialogues or assets pose a significant barrier to their wider implementation (Gry Online, 2025). Interdisciplinary research is necessary to develop standards for attribution and mechanisms for protecting creators' rights, utilizing tools such as Ubisoft's Ghostwriter (Ubisoft, 2024).

Second, it necessitates a more in-depth examination of the ethical implications of personalizing player experiences. AI algorithms analyzing behavioral data can lead to manipulative monetization mechanics, for example, by dynamically adjusting the game's difficulty based on users' spending tendencies (IEEE, 2023). An ethical framework is needed that balances the commercial goals of publishers with the protection of players' sensibilities, especially young people. The example of Ubisoft using "guardrails" to control NPC interactions (Ubisoft, 2024) can be a starting point for such analyses.

Third, it is worth examining the role of AI in creating cross-industry ecosystems. Integrating games with the music sector (virtual concerts in Fortnite) or film (interactive crossovers) requires advanced data analysis tools that will allow content to be tailored to the preferences of a diverse audience (Wang, 2023). The example of CD Projekt's collaboration with Respeecher

in voice reconstruction (Gry Online, 2023) suggests that AI can serve as a bridge between creative industries.

Finally, long-term studies of AI's impact on human creativity are necessary. Do tools such as Ubisoft's NEO NPC, which "co-creates" dialogues with scriptwriters (Ubisoft, 2024), enhance innovation or standardize the creative process? Answering this question requires monitoring the evolution of game designers' roles in the era of human-algorithm hybridization.

6. Summary

In summary, future research should combine technological and humanistic perspectives, considering both the potential of AI in optimizing business models and the risks associated with the obsolescence of traditional creative roles. As CD Projekt's cautious approach (Gry Online, 2025) demonstrates, success hinges on striking a balance between innovation and preserving the gaming industry's core values – creativity, engagement, and artistic authenticity. AI plays an increasingly important role in transforming gaming industry business models, introducing innovations in three key areas: optimizing production processes, personalizing player experiences, and creating new paths to monetization. Challenges related to copyright, algorithmic errors, and the ethics of personalization continue to be barriers to wider AI adoption. Nevertheless, these technologies open up new possibilities. The industry's future will depend on striking a balance between innovation and the responsible implementation of solutions that enhance creators' creativity, engage players, and uphold ethical norms. AI will not replace human intuition, but it will become its inseparable partner in shaping the next era of video games.

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MANAGING GREENHOUSE GAS AND DUST EMISSIONS IN THE POLISH HARD COAL MINING INDUSTRY

Andrzej CHMIELA[1], Beata BARSZCZOWSKA[2], Mirosław KINE[3], Małgorzata MAGDZIARCZYK[4], Eman Ibrahim ABDEL-WAHAB[5], Adam SMOLIŃSKI[6]

[1] Industrial Development Agency JSC, Katowice; andrzej.chmiela@katowice.arp.pl, ORCID: 0000-0002-0833-0923
[2] Katowice Business University, Katowice; Industrial Development Agency JSC, Katowice; beata.barszczowska@akademiagornoslaska.pl, ORCID: 0000-0001-6697-8683
[3] Industrial Development Agency JSC, Katowice; miroslaw.kine@katowice.arp.pl, ORCID: 0009-0000-5372-8909
[4] Opole University of Technology, Faculty of Economics and Management, Opole; m.magdziarczyk@po.edu.pl, ORCID: 0000-0003-1503-8469
[5] Food Legumes Research Department, Field Crops Research Institute, Agricultural Research Center (ARC), Giza, Egypt; Eman.abdel-wahab@arc.sci.eg, ORCID: 0000-0002-2277-7238
[6] Central Mining Institute - NRI, Katowice; asmolinski@gig.eu, ORCID: 0000-0002-4901-7546
* Correspondence author

Purpose: The purpose of this publication is to present the results of an original statistical analysis of the monitoring of environmental parameters of hard coal mining in Poland and to identify the reasons for changes in these parameters.
Design/methodology/approach: Planning safe and efficient hard coal mining requires continuous and ongoing analysis of the environmental parameters of mining operations. The presented analysis of selected environmental impacts of hard coal mining is based on information reported by mining companies. Data was obtained from the reports of mining companies and the website https://polskirynekwegla.pl/.
Findings: The cessation of coal mining will not fully stop greenhouse gas emissions from the previously mined deposit. This article analyzes changes in annual greenhouse gas and particulate matter emissions. The text identifies the most important reasons for the changes in the environmental impact of mining operations.
Research limitations/implications: The analysis was conducted for the period from 2013 to 2024. One small private Polish mining company does not report its indicators, so the data presented in the article only applies to other hard coal producers. However, due to the limited scope of this company's operations, the aggregated picture of the sector differs little from reality.
Practical implications: The presented analysis of selected environmental aspects of hard coal mining in Poland can help prepare a strategy adapting the hard coal mining sector to the dynamic changes in the fossil fuel market and new environmental challenges. Reducing greenhouse gas emissions by the EU, and thus by Poland, is necessary to slow the growth of unfavorable climate change.
Social implications: Halting, or even limiting, the ever-increasing global warming will be possible through the decarbonization transformation of economies.

Originality/value: The collected information on the environmental conditions of mining operations can help prepare potentially effective scenarios for the transformation of hard coal extraction in Poland and can also be used in the restructuring of mining in other countries.
Keywords: greenhouse gases, methane, hard coal mining, mining restructuring, decarbonization of the economy.
Category of the paper: Research paper, Case study.

1. Introduction

Mining is among the oldest and most essential industrial sectors. The sustainable operation of modern economies is inconceivable without uninterrupted access to mineral raw materials. (Hussein Salman, Abdulnbi Nayyef, 2024). Unfortunately, regardless of the mining model, mining always entails a serious environmental impact. Whether open-pit or underground mining, it impacts the atmosphere, hydrosphere, and lithosphere in various ways (Strzałkowski, Strzałkowska, 2023). The exploitation of deposits affects the environment not only during the period of active mining but also after its cessation (Chećko et al., 2022; Schuchová et al., 2023). Extracting raw materials to the surface along with waste rock using mining methods disrupts the integrity of the rock mass, for example, through fractures and the creation of post-mining voids after the selected deposit (Bąk et al., 2024; Shavarskyi et al., 2022). The resulting voids in the rock mass serve as zones for the disruption of previously entrapped gases, released via interconnected excavations, natural fractures, or hydraulic displacement. From these anthropogenic reservoirs, accumulating gases, mostly classified as greenhouse gases, can migrate to the surface through cracks or mine excavations (Wrona, 2017; Wrona et al., 2021). Impact on the atmosphere is usually associated with greenhouse gas emissions, primarily carbon dioxide and methane, released from mines in ventilation air. Greenhouse gas emissions from ventilation shafts are accompanied by continuous emissions of dust and thermal energy, but gases, smoke, and dust emitted from mine dumps and mining areas (e.g., access roads to dumps and storage areas) must also be considered in comprehensive environmental assessments. These factors stimulate the progression of unfavorable climate change (Bluszcz, Kijewska, 2016b). Unfortunately, the impact of mining activities on the environment is not confined to isolated environmental parameters. In practice, mining operations often interact with multiple environmental stressors simultaneously, amplifying their overall effect. (Strzałkowski, Strzałkowska, 2023).

Halting, or even limiting, the ever-increasing global warming will be possible through the decarbonization transformation of economies (Gawęda, 2022; 2024). Decarbonization assumes a gradual shift away from traditional high-emission technologies and aims to reduce greenhouse gas emissions into the atmosphere, including methane. One of the tools is to limit energy production from fossil fuels (Chećko et al., 2024; Khomenko, Jelonek, 2023). It must be

emphasized that the cessation of coal extraction activities does not eliminate residual methane emissions originating from previously mined coal seams (Bluszcz, Kijewska, 2016b; Bluszcz, 2019).

2. Methane emissions into the atmosphere

Global industrial activity exerts considerable pressure on climatic and environmental systems. The effects of this pressure are becoming increasingly evident, as climate change processes intensify at an accelerating rate. The global mineral extraction sector, which underpins industrial development, remains one of the principal contributors to environmental degradation (Chmiela, 2023; Du et al., 2024). Regardless of the type of mining activity, its operation is always associated with a serious environmental impact and usually with the unavoidable emission of greenhouse gases, including methane, into the atmosphere. Greenhouse gas emissions are generated primarily by the extraction, transport, and combustion of fossil fuels (Bąk et al., 2024; Korbiel, Czerwiński, 2022). Limiting the increase in average global temperature to 1.5°C above pre-industrial temperatures requires reducing carbon dioxide emissions, as well as emissions of other short-lived climate pollutants, including methane (Bluszcz et al., 2015; Sobczyk et al., 2020). Historically, methane was regarded as a relatively minor contributor to greenhouse warming. However, it is now recognized as a key driver of radiative forcing and short-term climate dynamics (Bazaluk et al., 2021; Biały et al., 2020). Although methane emissions are quantitatively lower compared to CO_2, this gas has a significantly higher greenhouse gas potential. Methane emissions are responsible for at least 25% of global warming (Jevell et al., 2014; Siciński, 2024). Reducing methane emissions can bring rapid climate benefits that cannot be achieved by reducing carbon dioxide emissions alone. Global methane emissions are estimated to have reached approximately 610 million Mg in 2024, of which approximately 60% were anthropogenic. In the global economy, agriculture emits approximately 41% of all emissions, the energy sector approximately 39%, and waste management approximately 18% (ARP, 2025; Skibski, 2025).

In recent years, both nationally and internationally, there has been increased activity aimed at reducing and monitoring greenhouse gas emissions, with particular emphasis on methane. In 2015, the signatories of the Paris Agreement agreed to achieve climate neutrality in the second half of the 21st century (Gawęda, 2022; 2024). The signatories of the Paris Agreement, responsible for approximately 55% of methane emissions in the global economy, committed to reducing methane emissions by at least 30% below 2020 levels by 2030. Such reductions may contribute to mitigating global warming and facilitate progress toward the objectives of the Paris Agreement, potentially curbing the projected rise in average global temperatures. The urgency of addressing greenhouse gas and methane emissions has been emphasized by the

European Commission, among others, through the adoption of the EU Methane Strategy and the European Green Deal (Bluszcz, Kijewska, 2016a; Sobczyk et al., 2022).

Reducing methane emissions by the EU, and thus by Poland, is necessary to achieve the goals of the Paris Agreement. In 2024, Poland's methane emissions into the atmosphere amounted to approximately 1.9 million Mg, which corresponds to approximately 7.5% of the methane emissions of the entire European Union (Barszczowska, 2024; Dragan, Zdyrko, 2023). The mining sector is the leading source of methane emissions in the national inventory, with emissions from hard coal mines accounting for approximately 51% of the national balance. Agriculture comes second with 32% of the total annual emissions (mainly livestock), and landfills come third with approximately 16% of emissions (Wrona, 2017; Wrona et al., 2021).

Complying with the adopted EU Methane Regulation will be a significant challenge for many Polish businesses, including mines. Despite Poland's relatively small share in global methane emissions into the atmosphere, the hard coal mining sector demonstrates high methane emission intensity (Gomółka, Kasprzak, 2023; Strzałkowski, Maruszczyk, 2024).

Another approach to combating methane hazards, and a way to reduce its potential for atmospheric emissions, is methane drainage and capture from disused mines. Such capture is characterized by marked fluctuations in methane flow rates and concentration levels, influenced by factors such as barometric pressure. Additional methane emissions may originate from decommissioned or abandoned mines that remain historically linked to the surface via networks of inactive shafts and natural geological conduits (Prusek, Turek, 2018; Sobczyk, Kopacz, 2018). Such pathways include decommissioned shafts, adits, old boreholes, faults, outcrops, and natural fractures in the rock mass. Released methane can utilize these migration pathways and enter the atmosphere. It should also be remembered that decommissioned or formerly abandoned mines lack any services capable of minimizing emissions or ensuring their occupational health and safety (Chmiela, 2022; Chmiela et al., 2023).

3. Research methods

The environmental impact of Polish hard coal mining presented in the text is based on information on hard coal mining reported by active mining companies in Poland. The data used for the analysis is available on the website https://polskirynekwegla.pl/ (ARP, 2025) administered by the Katowice branch of the Industrial Development Agency (ARP S.A.). In accordance with statistical obligations, hard coal mining entities report the scope of their mining operations to the Katowice Branch of the Industrial Development Agency (ARP S.A.). Based on the data received, ARP prepares statistical information for the minister on the mining operations of mining companies (Barszczowska, 2024; Prakash Pandey, Prasad Mishra, 2022).

Based on the scope and availability of data, mining companies conduct reporting on a monthly, quarterly, and annual basis. Among Polish mining entities, one privately held company does not disclose its operational data; however, due to its limited scale, this omission does not materially affect the overall sectoral analysis. Consequently, the presented statistical evaluation pertains exclusively to the remaining domestic hard coal producers.

Reported data occasionally reflects anticipated trends associated with sectoral restructuring of the hard coal mining sector and the ongoing energy transformation of the economy, while at other times unexpected and sometimes rapid changes in the assessed parameters occur. The aim of this publication is to present the results of an original statistical analysis of monitoring environmental parameters accompanying the restructuring process of the hard coal mining industry in Poland and to link the observed changes in parameters with the current political and economic situation in the country. The analysis was conducted for the period from 2013 to 2024 and identified the most important factors and events causing major changes in mining operations (Manowska et al., 2024; Schuchová et al., 2023).

Planning the safe and efficient extraction of mineral resources, including hard coal, requires ongoing analysis of the technical and economic parameters of mining operations. Data obtained from studies on environmental and economic conditions can inform the development of viable transformation strategies for domestic hard coal mining and may serve as a reference for restructuring efforts in other national mining sectors (Schuchová et al., 2023).

4. Restructuring of hard coal mining in Poland

According to official data, the historically highest hard coal production in Poland, just over 200 million Mg, was recorded in 1977. This "record" production level has never been repeated. The green transformation of the economy and the resulting restructuring of the hard coal mining sector have resulted in a systematic decline in hard coal production in Poland for years (Fig. 1) (ARP, 2025; Skibski, 2025). A "shadow of the sector's former glory" is the production of approximately 44 million Mg of thermal and coking hard coal at the end of 2024. Compared to the record mining production in 1977, this is slightly over 20% of that value (Smoliło et al., 2021). In 2024, approximately 4.4 million Mg less was extracted than in 2023 (a decrease of approximately 9% y/y). From 2013 to 2024, global production decreased by 42%, or 32.5 million Mg. On average, the hard coal mining industry reduces production by approximately 2.7 million Mg annually, or 3.5% year-on-year. Only once, in 2022, a steady decline in production was observed, with a slight increase (Fig. 1). This resulted from increased global demand for energy resources during the so-called economic rebound after the "COVID lockdown" period. In Poland, production increased by 0.6 million Mg (1 percentage point) (Górska, 2023; Khomenko, Jelonek, 2023). In 2024, Polish producers satisfied the economy's

demand for hard coal by approximately 89%, with the remaining volume obtained from imports (ARP, 2025; Skibski, 2025).

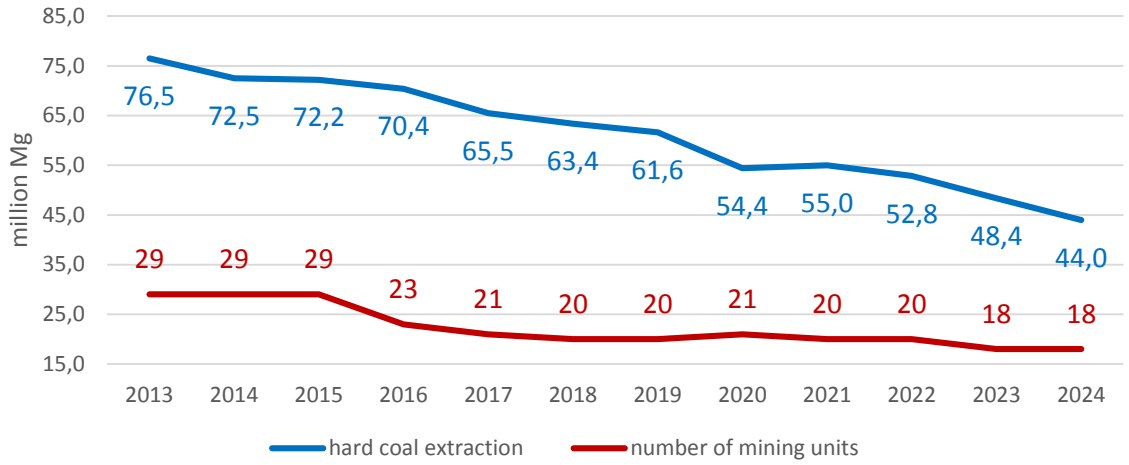


Figure 1. Volume of hard coal extraction in Poland [million Mg] against the background of the number of mining units.

Source: (ARP, 2025).

The Polish energy sector relies primarily on coal combustion for energy generation, for which it has adequate generation and transmission infrastructure. A hypothetical immediate closure of coal-fired units could undermine the country's energy security (Górska, 2023; Remiorz et al., 2025). Basing the energy sector on intermittent renewable energy sources may lead to operational disruptions, including blackouts, as evidenced by recent grid instability events across Europe. A transitional phase is essential to ensure a safe shift toward a low-emission economic model. During this relatively short transition period, traditional coal-fired power generation would stabilize energy supplies. The task of the restructured Polish hard coal mining industry would be to provide the necessary fuel for coal-fired units, with imports merely supplementing domestic production.

Given the expected decline in the domestic energy sector's demand for thermal coal and a similar lack of interest in thermal hard coal by other countries' economies, a reduction in mine production capacity is inevitable (Chećko et al., 2022; Siciński, 2024). Restructuring of the hard coal mining industry has been underway since the end of the 20th century. This process involves reducing the production capacity of active mines and gradually closing those deemed permanently unprofitable (Prakash Pandey, Prasad Mishra, 2022). According to the social contract (Agreement, 2021), the phased reduction of coal mines serving the energy sector will continue until 2049. The most unprofitable mines are to be liquidated first (Act, 2024). Deposits in active mining units are to be extracted efficiently and safely until the limit of their existence resulting from the social contract (Agreement, 2021).

Since 2013, there has been a decline in the number of active mining units. During this time, 12 mining units were closed. The social contract signed in 2021 provides for further reductions in domestic mining and the continued closure of unprofitable mining units (Strzałkowski,

Maruszczyk, 2024). In Poland, in 2024 (Figure 1), hard coal mining was conducted by eight state-owned and private mining companies, using 18 mining units (ARP, 2025; Skibski, 2025).

The ongoing restructuring processes and adaptation of the sector to a zero-emission economic model limit mining capacity, which should affect the ecological aspects of mining operations (Abdulnbi Nayyef et al., 2024; Magdziarczyk et al., 2023). Along with the restructuring of hard coal mining, a gradual shift away from traditional high-emission technologies and a reduction in emissions of greenhouse gases, dust and heat into the atmosphere is expected (Bluszcz, 2019; Sobczyk et al., 2020).

5. Results and discussion

Due to the volume of hard coal production, Poland is the largest methane emitter in the European Union. In 2024, Polish mining produced approximately 96% of the total hard coal production in the EU, followed by Romania and the Czech Republic. In Polish hard coal mining, methane emissions are primarily related to mining operations. Combating methane hazards in mines involves ventilation dilution of gas released into the excavations and methane drainage of coal seams and adjacent rocks (Biały et al., 2020; Bluszcz, Kijewska, 2016b). Unfortunately, for safety reasons for the crew and the mining plant, methane released into the excavations is diluted through ventilation and released into the atmosphere through a network of ventilation shafts. Its capture is difficult or even technically impossible due to its low concentration, up to 0.75% in mine exhaust shafts (Abdulnbi Nayyef et al., 2024; Khomenko, Jelonek, 2023). In rock mass methane drainage, most often achieved by creating negative pressure, methane drainage systems capture methane through a system of special pipelines or excavations and direct it to the surface for management. It is assumed that for Polish mining, the proper efficiency of methane drainage from coal seams and adjacent rocks using drainage systems should be at least 50%, while the economic utilization of the captured methane should be at least 95%.

Hard coal deposits are typically mined from the top down. According to this principle, seams located closer to the surface are first selected (Strzałkowski, Strzałkowska, 2023). Due to their proximity to the surface, the deposit undergoes spontaneous degassing over time. Progressive mining reaches deeper and deeper, where the deposits are characterized by higher gas content. Typically, as the deposit is mined and the resulting depth increases, the amount of greenhouse gases released during extraction increases. In hard coal mines, the deposit most often releases carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), hydrogen sulfide (H_2S), sulfur oxides (SO_x), and nitrogen oxides (NO_x). These gases are released from the deposit and originate from natural oxidation processes or are a result of technological processes related to mining. Greenhouse gas emissions from mines are primarily based on two gases: carbon

dioxide (CO_2) and methane (CH_4). It is estimated that virtually all of the methane emitted into the atmosphere is released from coal and adjacent rocks, originating from natural processes in deposit formation (Wrona, 2017; Wrona et al., 2021). CO_2 emissions result primarily from the release of gas trapped in the rock mass, but also from the natural oxidation of coal upon contact with ventilation air. Although the concentrations of other gases are relatively low, the large volumes of ventilation air circulating through mines result in substantial absolute emissions. Sulfur oxides (SO_x) and nitrogen oxides (NO_x) emitted into the atmosphere by mines, most often result from blasting operations using explosives and the combustion of liquid fuels by mine equipment. CO emissions may result from incomplete combustion of coal in goaf or liquid fuels with insufficient oxygen supply. Hydrogen sulfide emissions typically originate from the decay of organic substances, such as wood. Hydrogen sulfide also occurs in aquifers, where, in addition to organic matter decomposition, microbial conversion of sulfates can occur. The possibility that this process may be enhanced by the presence of ammonia cannot be ignored (Bazaluk et al., 2021).

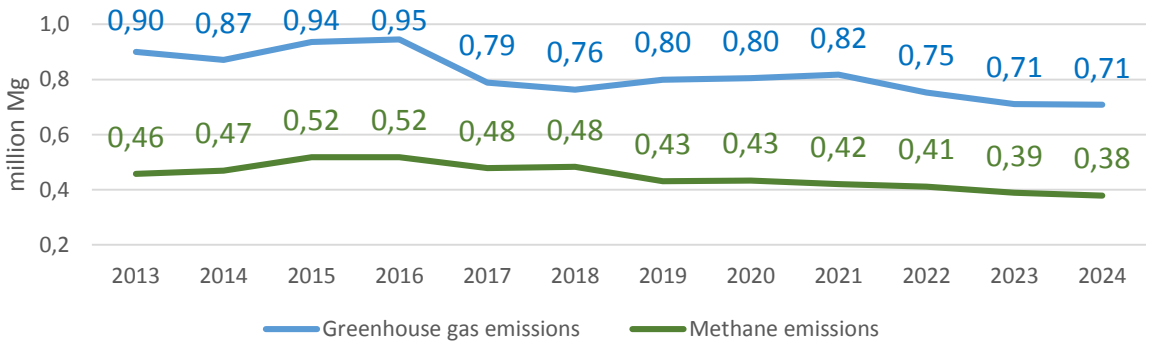


Figure 2. Greenhouse gas emissions (including methane) and methane emissions from hard coal mining in Poland [million Mg].

Source: (ARP, 2025).

Greenhouse gas emissions have been declining since 2013. During the analyzed period, a decrease was recorded from approximately 0.9 million Mg in 2013 to approximately 0.71 million Mg in 2024 (Figure 2). As illustrated in Figure 2, the analyzed period saw an absolute decrease in greenhouse gas emissions by approximately 21%. In 2015 and 2016, a temporary increase in hard coal mining emissions was observed. This increase resulted from mines exploring new gas-bearing, yet not yet degassed, seams. Appropriate prevention led to a return to the previous downward trend. During the same period, absolute methane emissions to the atmosphere (Figure 2), after initially stabilizing at approximately 0.47 million Mg and increasing in 2015 and 2016 to approximately 0.52 million Mg, have been gradually declining. In 2024, emissions amounted to approximately 0.38 million Mg, approximately 19% lower than in 2013. The increase in greenhouse gas discharge in 2021 to 0.82 million Mg/year is difficult to explain. The increase in greenhouse gas emissions is certainly partly due to increased extraction, but the growth rate of greenhouse gas emissions (2.5% year-on-year) significantly

exceeds the growth rate of extraction (1.1% year-on-year). A partial explanation may be the fact that, for COVID-19 prevention reasons, within the limits of available technical capabilities, some mines increased the intensity of excavation ventilation in the second half of 2020 and early 2021. However, the question remains whether even increased mine ventilation could increase greenhouse gas emissions sufficiently without increasing methane emissions. Additionally, unlike the increase in global greenhouse gas emissions from hard coal mining, no increase in methane emissions into the atmosphere was observed in 2021. Paradoxically, methane emissions into the atmosphere decreased by 2.3% year-on-year in 2021.

As previously discussed, greenhouse gas emissions, including methane, depend on two key factors. One is the steadily declining global hard coal production which theoretically contributes to lower emission volumes. The other is the increasing gas content of mined deposits due to greater mining depths, which tend to elevate emission levels. To evaluate the specific emissions, the total gas and methane emissions reported by the sector were divided by the annual mining production also reported by mining companies (Fig. 3). During the analysis period from 2013 to 2024, specific greenhouse gas emissions per unit of coal extracted have shown a consistent upward trend. There was an increase from 11.8 kg/Mg in 2013 to 16.1 kg/Mg in 2024, which corresponds to a 27% increase. In the analyzed period, the Polish hard coal mining industry emitted on average 13.4 kg of greenhouse gases per Mg of hard coal extracted (ARP, 2025; Skibski, 2025).

During the analyzed time period, the average methane emission per Mg of hard coal mined in Poland was 7.4 kg/Mg, and the variability also showed an upward trend. From 2013 to 2024, specific methane emission increased from 6.8 to 8.6 kg/Mg (ARP, 2025; Skibski, 2025). The increase in specific methane emission is attributable to the exploitation of increasingly deeper and more methane-rich coal seams.

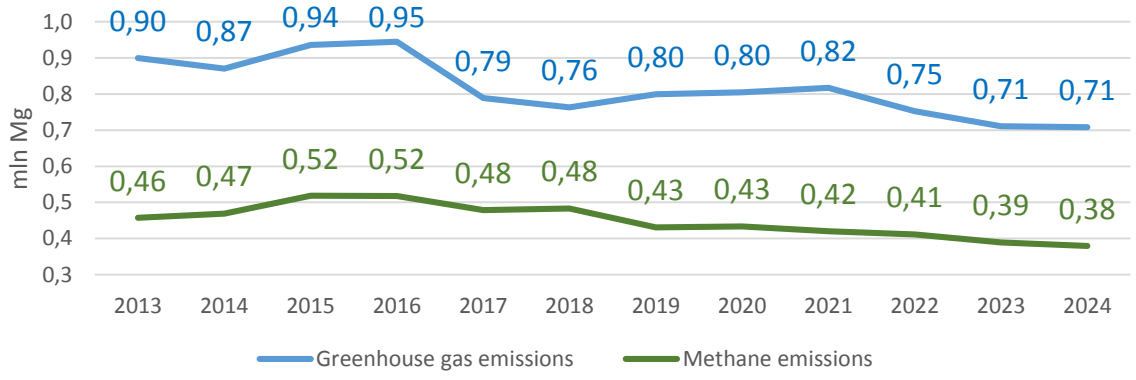


Figure 3. Unit greenhouse gas emissions (including methane) and methane emissions alone from hard coal mining.

Source: (ARP, 2025).

To better illustrate the emissions intensity of hard coal mining, the specific greenhouse gas and methane emissions per mining unit were calculated (Bluszcz, 2019; Górska, 2023). Emissions and the number of mining units were obtained from data reported by coal companies. The number of mining units reported by coal companies is imperfect for direct comparisons. Among the mining units reporting their data, there are single- and multi-unit mines, which are treated equally in this comparison (Prusek, Turek, 2018; Sobczyk et al., 2022). Bearing in mind that different numbers of operations, or component mines, may distort the comparison, some analysis of the trends can be achieved.

In the first years of the assessed period, from 2013 to 2024, greenhouse gas emissions per active mining unit were around 30,000 Mg/year (Fig. 4). Due to the early decommissioning of several mining units, a significant increase in greenhouse gas emissions per mining unit has occurred since 2016, reaching approximately 39,000 Mg/year, a level that has persisted to this day (ARP, 2025; Skibski, 2025). This significant increase can be explained by the fact that the decommissioned mining units had relatively low production and were exploiting a deposit that was already largely degassed. Notably, a significant increase in emissions per mining unit was observed in 2021. Greenhouse gas emissions reached approximately 40,900 Mg/mining unit/year, 6% more than in 2020 and 8% more than in 2022 (Fig. 4). As mining operations extend to greater depths and deposits become increasingly unfavorable for extraction, it is statistically expected that emissions per unit may rise. Merely limiting extraction volumes may not be sufficient to reverse this trend.

In the case of average methane emissions by a mining unit, apart from the varying number of movements within a mining unit, the analysis may be complicated by the fact that some units emit negligible amounts of methane, resulting in significant deviations between actual and average values. Under these assumptions, from 2013 to 2015, the average mining unit emitted approximately 17,000 Mg CH_4/mining unit/year (Fig. 4). Due to the closure of several non-methane mines, average mining unit emissions have been increasing since 2016 to approximately 23,000 Mg CH_4/mining unit/year. In subsequent years (from 2019), methane emissions have decreased to approximately 21,000 Mg CH_4/mining unit/year, which is still maintained (Fig. 4) (ARP, 2025; Skibski, 2025). This decline may be due to the sector's reduction in hard coal production and mines preparations for implementing the provisions of the EU methane regulation. Due to the restrictive provisions of the aforementioned regulation, it should be expected that emissions from mining units should decrease or at least not increase.

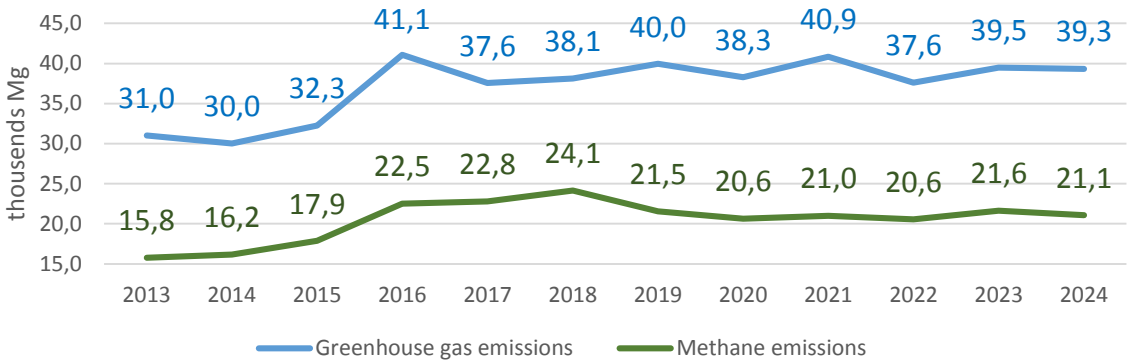


Figure 4. Greenhouse gas emissions (including methane) and methane emissions per hard coal mining unit.

Source: (ARP, 2025).

Due to their utility and independence from energy sources, modern underground mining often employs mining machinery powered by engines burning liquid fuels. While the specific emissions of a single machine are relatively low, the total amount of diesel fuel consumed can be a significant source of greenhouse gases. Until 2017, approximately 9500 Mg/year of diesel fuel was burned in the Polish hard coal mining industry (Fig. 5). Since 2018, average diesel fuel consumption in hard coal mines has increased to over 11,000 Mg/year. This level has remained constant. In 2024, the total diesel fuel consumption across all hard coal mining units was approximately 655,000 Mg, used to power combustion-driven mining machinery. As with the analysis of hard coal mining emissions, the increase in diesel fuel consumption in 2021 to approximately 11,900 Mg is difficult to explain (Fig. 5) (ARP, 2025; Skibski, 2025). This could be explained by the significant dispersal of workers to various tasks temporarily suspended in 2020 due toCOVID-19 restrictions. Performing various mining or repair tasks scattered throughout the mine by small groups of workers could have required the consumption of increased volumes of diesel fuel by combustion-powered means of transport, such as suspended monorails. Another contributing factor may have been less stringent fuel management practices following the lockdown period, resulting in inefficient fuel utilization.

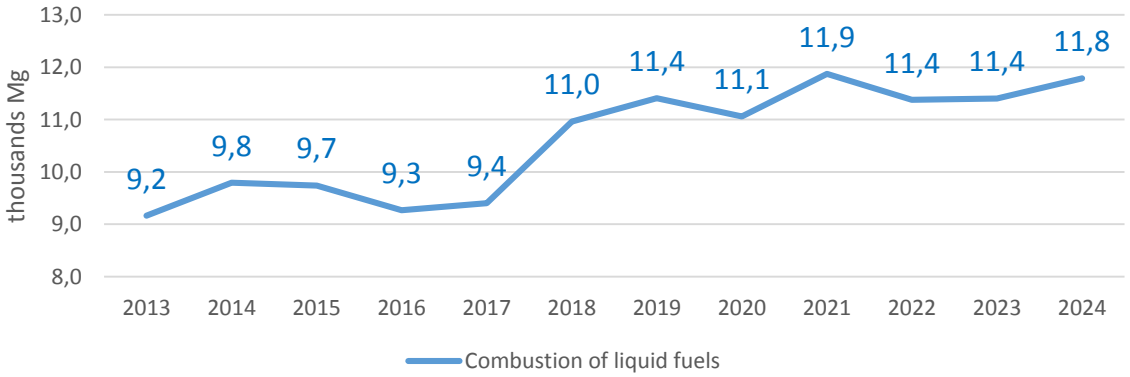


Figure 5. Combustion of liquid fuels (diesel oil) by mining machines.

Source: (ARP, 2025).

The carbon footprint of diesel fuel combustion in engines, which is the amount of carbon dioxide (CO_2) emitted into the atmosphere during operation, is approximately 2.68 kg of CO2 per liter of fuel. In addition to direct CO_2 emissions, diesel fuel combustion also generates other pollutants such as sulfur oxides (SO_x/SO_2), nitrogen oxides (NO_x/NO_2), carbon monoxide (CO), total particulate matter (TSP), and soot. The maximum sulfur content in diesel fuel in the European Union is 10 mg/kg (10 ppm). This limit is intended to reduce harmful sulfur oxide emissions into the atmosphere and limit corrosion in engines. According to the data from liquid fuel producers on the emission intensity of diesel oil combustion and assuming that 1 Mg of diesel oil is approximately 1220 liters, it can be calculated that in 2024, as a result of the operation of combustion engines in hard coal mines, 38,500 Mg of carbon dioxide (CO_2), 71 Mg of nitrogen oxides (NO_x/NO_2), 5.7 Mg of carbon monoxide (CO), up to 0.3 Mg of sulfur oxides (SO_x/SO_2), and 14.2 Mg of suspended particulate matter (TSP) were emitted (ARP, 2025; Skibski, 2025).

During the extraction of mineral deposits, including hard coal, dust is generated. Some dust remains in the mine, but some is released to the surface with ventilation air. In addition to dust resulting from mining, ventilation air also carries away types of dust The largest fraction of these is limestone dust (commonly referred to as stone dust), which is used to prevent coal dust explosions. Since 2013, dust emissions from hard coal mines have been decreasing (Fig. 6). During the analyzed period, dust emissions decreased from 1603 Mg in 2013 to 685 Mg in 2024. This represents a total reduction of 918 Mg, or 57%, with an average annual decrease of approximately 83 Mg (ARP, 2025; Skibski, 2025).

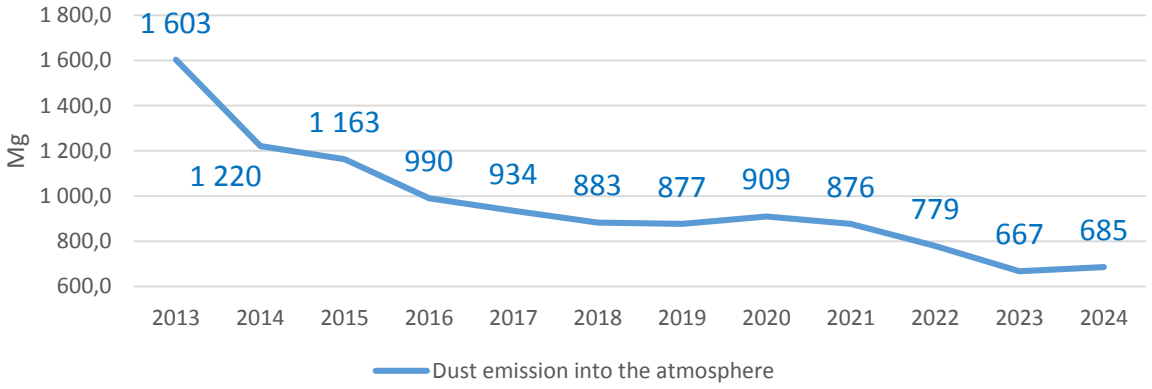


Figure 6. Dust emission into the atmosphere by hard coal mining.
Source: (ARP, 2025).

Mechanization of mining and the expansion of mines into increasingly thinner seams may increase dust levels in mines relative to production volume, but reduced production will reduce total dust emissions into the atmosphere (Fig. 7). Between 2013 and 2016, there was a rapid decline in specific atmospheric dust emissions, most likely due to the closure of the least efficient mines. Following this period, dust emissions stabilized at approximately 15 Mg per million Mg of hard coal produced. Notable exceptions occurred in 2020 and 2021

(Mozharovskyi et al., 2025; Redziuk, 2022; Shekhunova et al., 2023), when specific dust emissions to the environment increased (ARP, 2025; Skibski, 2025).

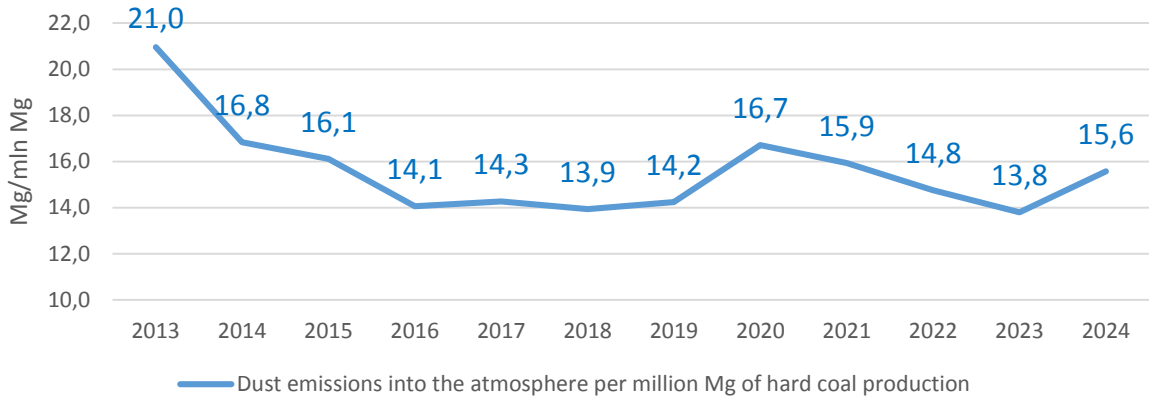


Figure 7. Dust emissions into the atmosphere per million Mg of hard coal production.
Source: (ARP, 2025).

The average dust emission into the atmosphere resulting from mining operations conducted by a mining unit remained at a level of approximately 43 Mg until 2021. Following the closure of two mining units in 2022, the situation stabilized, and currently the average hard coal mining unit emits approximately 38 Mg of various dust annually (Fig. 8) (ARP, 2025; Skibski, 2025).

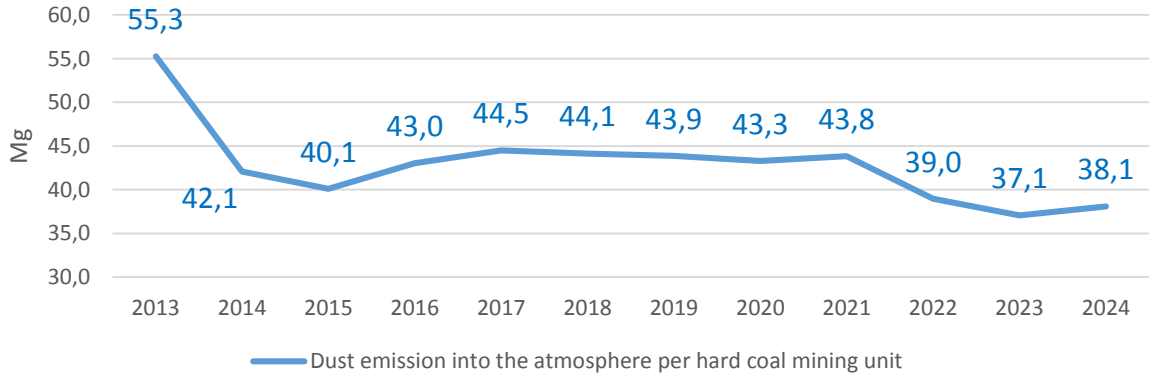


Figure 8. Dust emission into the atmosphere per hard coal mining unit.
Source: (ARP, 2025).

The Polish economy, and especially the energy sector, is largely based on hard coal combustion. Transforming both the economy and the energy sector is a long-term process. An immediate shift away from hard coal combustion would undermine the foundations of energy security. A transition period will be necessary, during which the Polish coal mining industry will continue to supply the necessary fossil fuels. Unfortunately, mining will be accompanied by ongoing emissions of greenhouse gases and particulate matter into the atmosphere, and even an immediate cessation of mining operations would not bring about rapid improvement.

6. Conclusions

Efforts to limit global warming to 1.5°C or 2°C above pre-industrial levels will require rapid and sustained reductions in emissions of carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and other greenhouse gases. This includes electrifying the economy, deploying renewable energy sources, improving efficiency, and using negative emissions technologies such as CCUS. These climate mitigation measures rely on technologies that reduce emissions at source as well as those that remove greenhouse gases already present in the atmosphere.

Conducting any mining activity always entails a significant environmental impact. The scale of ecological changes most often depends on the type of mineral being extracted and the scope of its extraction. The decline in economic demand for fossil fuels, including thermal coal, resulting from the industry's adaptation to climate and energy policies and the decarbonization of the energy sector, is reflected in the restructuring of the hard coal mining sector as a whole, and thus in its environmental impact. Hard coal production is adjusted to the needs of the economy. An immediate cessation of mining is impossible, as the Polish energy sector relies on coal combustion. A transition period is necessary to ensure the country's energy security. It is estimated that coal will be present in the Polish energy sector until at least 2050. The Polish hard coal mining industry, based on a support system, is tasked with providing the necessary volumes of hard coal.

A new hard coal mining policy and the resulting legal regulations should be part of a broader policy of transforming the fossil fuel sector. Forecasts assume a decline in demand for thermal coal, which necessitates the integration of climate, energy, and industrial policies into a unified strategy. Mitigating the effects of rising average global temperatures resulting from broader climate policy requires reducing greenhouse gas and particulate matter emissions into the atmosphere. Carbon dioxide is typically understood as a greenhouse gas, but methane plays a significant role in atmospheric warming mechanisms. Reducing production capacity in the Polish hard coal mining industry lowers greenhouse gas emissions. In 2024, hard coal mining released approximately 0.71 million Mg of greenhouse gases into the atmosphere, including approximately 0.38 million Mg of methane.

Due to the reduction in production capacity in the hard coal sector, absolute emissions of greenhouse gases, including methane, resulting from mining operations are decreasing. Unfortunately, the decline in production and the decreasing number of mining units do not correspond to the reduction in gas emissions. Due, among other things, to the exploration of ever deeper deposits, their gas content is increasing. The exploitation of more gas-rich deposits translates into higher specific greenhouse gas emissions per extraction volume. Since 2013, greenhouse gas emissions per extraction unit have increased by approximately 33%, and methane emissions by approximately 43%. Since 2016, greenhouse gas and methane emissions per extraction unit have remained more or less constant at 39.3 thousand Mg of greenhouse gases, including 21.1 thousand Mg of methane.

Airborne dust emissions from hard coal mine ventilation shafts are declining, with a decrease of approximately 57% recorded between 2013 and 2024. The decline in total dust volume was greater than the decline in extraction volume. From 2014 to 2024, dust emissions per extraction volume remained more or less constant at approximately 15 Mg/million Mg of extraction. However, emissions per mining unit, after remaining stable for a long time, fell to approximately 38 Mg per mining unit in 2022, a level that remains unchanged.

The end of coal mining will not fully halt greenhouse gas and methane emissions from the previously mined deposit. Emissions will remain directly from the once-mined deposit through the system of fractures and faults, and indirectly from the abandoned mine infrastructure. At least residual emissions should be expected for many years after mining ceases. In contrast, in the case of dust, the end of mining will be equivalent to the end of dust emissions into the atmosphere, provided that the landfills where secondary dust emissions occur are reclaimed.

Methane emissions are a significant component of the global greenhouse effect. The potential for methane (CH_4) to rapidly impact the climate and the potential technical feasibility of reducing its atmospheric emissions make it one of the most effective short-term climate policy goals. For Poland, this means accelerating the implementation of EU regulations. In the Polish mining industry, methane has traditionally been perceived as an unwanted gas co-occurring in coal seams, posing a threat to the safety of both people and mines. The potential for reducing methane emissions should not be viewed as a cost, but through the possibility of its management under favorable conditions, as a tool enabling sustainable restructuring of the sector.

The greenhouse gas emission rates analyzed in this study in Polish hard coal mines are only partially due to the restructuring of the sector and the shift to more difficult-to-extract deposits. Urgently addressing the escalation of the presented problems in greenhouse gas emissions into the environment could improve the efficiency of the hard coal mining sector.

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COMMODITY MARKET SIGNALS: COMMODITIES AS LEADING INDICATORS FOR THE WIG INDEX

Bartosz CHORKOWY

Uniwersytet Opolski; bchorkowy@uni.opole.pl, ORCID: 0000-0003-0349-319X

Purpose: This article investigates the potential of selected commodities as leading indicators for the WIG stock index in Poland during the period 2017-2022.
Design/methodology/approach: The analysis examines the relationships between logarithmic returns of commodities—including Brent crude oil, industrial metals, and precious metals—and the logarithmic returns of the WIG index, both contemporaneously and with lags of up to 252 trading sessions.
Findings: The findings reveal a strengthening correlation over time between the industrial commodities market and the Polish equity market. The highest and statistically significant coefficients were observed for copper, zinc, aluminum, and crude oil, particularly at lags of 1 to 3 days. Precious metals such as gold and silver exhibited weak and often statistically insignificant relationships with the WIG index, confirming their defensive nature.
Practical implications: These results suggest that price changes in selected commodities may provide valuable leading signals for the Polish stock market, with potential applications in forecasting models and investment strategies.
Originality/value: The study makes an important contribution to understanding the mechanisms of interdependence between the commodity market and the capital market in the context of an open economy.
Keywords: WIG, commodities, correlation, leading indicators, capital market.
Category of the paper: Research paper.

1. Introduction

Commodity markets play a crucial role in the global financial system and the real economy, serving both as sources of risk and as leading signals for investors and policymakers. Over the past two decades, increasingly close linkages between financial and commodity markets have emerged, driven by trade globalization, the development of derivatives, and the rising importance of commodities as investment assets. In emerging economies such as Poland, these linkages may carry significant implications for both economic policy and capital market investment strategies. Prior studies suggest that commodity prices may serve as leading

indicators of economic conditions and stock market performance (Tang, Xiong, 2012; Creti et al., 2013; Büyükşahin et al., 2010). Their predictive power stems from their tight connection to the business cycle, inflation, and global industrial demand. Nevertheless, the nature of these relationships is often complex and context-dependent, varying by asset class, geographic region, and time horizon. While much of the literature addresses developed markets, the interdependencies between commodities and the Polish capital market remain relatively underexplored (Baffes, Haniotis, 2010).

The WIG index, as a broad benchmark for the Warsaw Stock Exchange, represents an important barometer of investor sentiment and the state of the economy. Against this backdrop, the question arises as to whether commodity price movements—such as those of copper, gold, crude oil, or aluminum—can serve as leading indicators of future changes in the WIG index. This issue is of relevance both to institutional investors and to regulators monitoring potential sources of volatility and systemic risk.

The purpose of this paper is to analyze the correlation structure between logarithmic returns of the WIG index and selected commodity markets, accounting for time lags of up to one year. The lag analysis makes it possible to assess whether changes in commodity markets precede changes in the WIG index, which would indicate the potential for their use in forecasting and investment strategies. This study fills a gap in the literature by providing new empirical evidence for the Polish capital market, offering both practical and theoretical insights into the integration of commodity and financial markets in Central and Eastern Europe.

2. The Commodity Market and the Capital Market in the Light of Financial Literature

The relationships between commodity and stock markets have long attracted the attention of financial literature. Numerous studies indicate that commodity prices reflect economic fundamentals and may serve as leading signals for capital markets, which is particularly relevant in the context of portfolio investment, risk management, and economic policy. Tang and Xiong (2012) emphasize that the growing financialization of commodity markets has led to stronger correlations with equity markets, especially during periods of heightened financial uncertainty. Similar conclusions are presented by Creti et al. (2013), who show that the volatility of stock and commodity markets is significantly interconnected, with the strength of these relationships varying over time. Büyükşahin et al. (2010) analyze the influence of market fundamentals and speculative investor activity on commodity futures prices, pointing to the increasing integration of commodity and broader financial markets. Likewise, Baffes and Haniotis (2010) highlight the macroeconomic consequences of sharp commodity price fluctuations, underscoring their importance as potential leading indicators of economic activity.

Strong linkages between commodities and equities in the context of global capital flows are also documented by Silvennoinen and Thorp (2013), who note an intensification of correlations during financial crises. In a now-classic study, Pindyck and Rotemberg (1990) demonstrated that commodity prices often move together in ways not fully explained by supply and demand fundamentals, suggesting the presence of common financial factors. Mensi et al. (2013) and Reboredo (2012) investigate the relationships between commodity and stock markets using copula models, finding significant but time-varying dependencies across different phases of the business cycle. Dyhrberg (2016) shows that some assets, such as gold and oil, can serve as hedges against equity markets under certain market conditions.

In the Polish literature, this topic is addressed by, among others, Pietrzak (2014), who examines correlations between precious metal prices and the Polish stock market, pointing to their potential use in portfolio risk management. Misztal (2013) analyzes the effect of commodity prices on WIG index volatility, stressing the importance of leading effects in investment policy. Borowski (2019) focuses on the interdependencies between the crude oil market and selected sectors of the Warsaw Stock Exchange, identifying significant linkages, particularly in the industrial and chemical sectors. Świderska (2017) explores the relationships between energy commodity prices, the Polish economy, and the capital market, noting that in certain periods commodity prices may function as leading indicators for the domestic equity market.

Park and Ratti (2008) examine the relationship between crude oil prices and stock indices, pointing to the negative impact of oil price shocks on equity markets. Hamilton (2009) offers a broader analysis of oil's influence on the economy, emphasizing the role of energy commodities in transmitting economic shocks to financial markets. Creti et al. (2014) find that industrial metals—particularly copper—play a significant role as leading indicators of economic activity, which may translate into their relationship with stock indices. Daskalaki and Skiadopoulos (2011) argue that including commodities in investment portfolios can reduce risk, although correlations may rise under crisis conditions. Batten et al. (2010) study the role of gold as a "safe haven", suggesting its negative correlation with stock markets in times of elevated risk. Alquist and Kilian (2010) examine the predictability of crude oil prices, which has direct implications for equity investors. Gilbert (2010) highlights the increasing role of financial investors in shaping commodity prices, thereby reinforcing the potential interconnections between these markets.

Despite the extensive international literature, relatively few studies have concentrated on lagged relationships between commodity and stock markets in Central and Eastern Europe, including Poland. This study addresses this gap by analyzing the relationships between logarithmic returns of the WIG index and selected commodities, incorporating time lags of up to one year.

3. Data and Methodology

3.1. Data

The analysis covered daily quotations of the WIG stock index and selected commodities over the period from January 2010 to May 2025. The data were drawn from publicly available databases and consist of time series obtained from official sources, including the Warsaw Stock Exchange, Bloomberg, and other financial market databases. The scope of the study was limited to assets of substantial economic and investment importance, both in Poland and globally. The following assets were included: WIG – a broad stock market index in Poland serving as a benchmark for the Warsaw Stock Exchange, gold, silver, copper, platinum, Brent crude oil, natural gas, and aluminum. Commodity quotations are expressed in U.S. dollars per unit of measurement appropriate for the given instrument (e.g., ounce, barrel, metric ton), while WIG quotations are denominated in Polish zloty. To ensure comparability, logarithmic rates of return were applied, eliminating the influence of differing nominal units of measurement.

The transformation of data into logarithmic returns was carried out for several methodological and economic reasons. First, asset price levels are quoted in different currencies (e.g., Polish zloty for the WIG index, U.S. dollars for commodities) and in different measurement units (e.g., ounces, barrels, metric tons). Comparing their nominal values would therefore be unjustified and would not allow for the assessment of true interdependencies between these instruments. Rates of return resolve this issue by converting data into a common percentage scale, enabling direct comparison. Second, logarithmic returns provide superior statistical properties for time series. They tend to approximate a normal distribution more closely than arithmetic returns, which is particularly important when applying statistical methods based on the assumption of normality, such as tests of significance for Pearson correlation coefficients. Third, logarithmic returns are additive over time, meaning that the cumulative return over period T can be expressed as the sum of daily returns. This greatly simplifies the analysis of lag structures and long-term dynamics. Additionally, logarithmic transformation reduces the impact of outliers, which may disproportionately distort correlation estimates.

For these reasons, transforming data into logarithmic returns is a standard procedure in financial analysis and was applied in this study to enhance the reliability and comparability of results.

3.2. Data Transformation

For the purposes of the study, daily logarithmic rates of return were calculated using the following formula:

$$r_t = \ln\left(\frac{P_t}{P_{t-1}}\right) \tag{1}$$

where:
r_t – the return on day t,
P_t – price or index value on day t.

In the case of missing data on days when the market was closed (e.g. stock exchange holidays), observations were removed synchronously so that each data pair (WIG – commodity) covered the same trading days. Outliers exceeding four standard deviations from the mean were removed.

3.3. Methodology

The study consists of two stages: calculating the correlation between the WIG return rate and selected commodities, and calculating the correlation with delays.

In the first stage, Pearson's correlation coefficients were determined between the daily logarithmic rates of return of the WIG index and each time series of the selected commodity without delays. The calculations were performed separately for each year. The significance of the correlation coefficients was assessed using Student's t-test according to the formula:

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

where:
r – Pearson's correlation coefficient,
n – number of observations.

The t-statistic values were compared with the critical values of the Student's t-distribution at a significance level of $\alpha = 0.05$.

In the second stage, lag correlation analysis was performed to identify potential leading relationships between commodity markets and the WIG index. Pearson's correlation coefficients were calculated for each commodity using the following formula:

$$\rho_{lag} = \mathrm{corr}(WIG_t,\ S_{t-k}) \tag{3}$$

where:
WIG_t – return on the WIG index on day t,
S_{t-k} – raw material return rate on day $t-k$,
k – number of days of delay (lag), from 0 to 252 days (i.e. up to one session year).

The calculations were performed for each raw material with a lag shifted by one day in order to capture the full picture of leading relationships. Correlation coefficients were assessed for statistical significance in the same way as for correlations without lags.

3.4. Limitations

It should be emphasized that the correlation coefficients obtained do not imply causal relationships, but merely the co-movement of price dynamics. An additional limitation arises from the influence of external factors, such as the USD/PLN exchange rate, which may alter the strength of the relationships between commodity markets denominated in U.S. dollars and the WIG index expressed in Polish zloty. Nevertheless, the applied methodology makes it possible to identify both static and dynamic linkages between the commodity market and the equity market in Poland, thereby allowing for verification of the hypothesis that commodity markets provide leading signals for the WIG index.

4. Results

4.1. Contemporaneous Correlations

The analysis of correlations without lags revealed varying degrees of linkage between daily logarithmic returns of the WIG index and selected commodities. The results are presented in Table 1. Pearson correlation coefficients are reported to two decimal places. Statistically significant values are highlighted in green.

The analysis of correlations between the logarithmic returns of the WIG index and commodity prices in 2017-2022 reveals clear linkages between the equity market and the segment of industrial metals as well as crude oil. The strongest and consistently statistically significant relationships were observed for copper, whose correlation coefficients increased over the period from 0.28 in 2017 to 0.51 in 2021, confirming its role as a key indicator of economic activity. Brent crude oil likewise exhibited significant positive associations with the WIG, particularly in 2020-2022, with coefficients in the range of 0.41-0.47, which may reflect the growing importance of the energy sector in the Polish economy. Aluminum and zinc, similar to copper, showed an upward trend in their correlations with the stock market, suggesting an increasing sensitivity of the Warsaw Stock Exchange to the volatility of industrial commodity markets.

Table 1.
Contemporaneous correlations between WIG returns and selected commodities

Commodity	2017	2018	2019	2020	2021	2022
Brent crude	**0.21**	**0.24**	**0.29**	**0.41**	**0.47**	**0.44**
Copper	**0.28**	**0.31**	**0.37**	**0.49**	**0.51**	**0.48**
Gold	-0.04	0.02	0.00	0.06	0.10	0.09
Silver	-0.04	0.01	-0.02	0.03	0.05	0.04
Palladium	**0.16**	**0.18**	**0.21**	**0.19**	**0.18**	**0.17**
Platinum	0.05	0.07	0.12	0.10	0.11	0.09
Nickel	0.10	**0.15**	**0.15**	**0.20**	**0.22**	**0.21**

Cont. table 1.

Aluminum	**0.16**	**0.20**	**0.23**	**0.31**	**0.38**	**0.37**
Zinc	**0.19**	**0.26**	**0.28**	**0.33**	**0.39**	**0.34**
Lead	0.02	0.03	0.05	0.08	0.10	0.07
Tin	0.10	0.12	0.09	**0.14**	**0.22**	**0.20**

Source: Own elaboration.

By contrast, precious metals such as gold and silver displayed weak and generally statistically insignificant correlations with the WIG, indicating their function as defensive assets largely independent of stock market conditions. Palladium, nickel, and tin demonstrated moderate yet significant relationships, particularly during periods of heightened market volatility. These findings suggest that changes in the prices of selected commodities may serve as valuable leading indicators for the Polish equity market, especially in the context of industrial metals and crude oil.

4.2. Lagged Correlations

Far more interesting results were obtained in the lagged correlation analysis, the aim of which was to identify potential leading signals transmitted from the commodity market to the equity market in Poland. For each commodity, Pearson correlation coefficients were calculated between WIG returns and commodity returns shifted in time (lag) from 0 to 252 days. Table 2 presents the highest correlation coefficients (absolute values) obtained within this range for each commodity.

Table 2.
Three highest correlation coefficients between logarithmic WIG returns and logarithmic commodity returns with corresponding lags

Commodity	Lag (days)	Correlation
Brent crude	2	0.314
Brent crude	3	0.297
Brent crude	1	0.268
Copper	2	0.395
Copper	1	0.361
Copper	3	0.352
Gold	7	0.107
Gold	5	0.098
Gold	6	0.092
Silver	8	0.101
Silver	4	0.095
Silver	5	0.089
Palladium	4	0.202
Palladium	3	0.193
Palladium	2	0.185
Platinum	5	0.123
Platinum	2	0.104
Platinum	4	0.097
Nickel	2	0.232
Nickel	3	0.218
Nickel	1	0.191

Cont. table 2.

Aluminum	2	0.342
Aluminum	3	0.319
Aluminum	1	0.305
Zinc	2	0.363
Zinc	1	0.319
Zinc	3	0.307
Lead	6	0.107
Lead	5	0.097
Lead	3	0.092
Tin	2	0.186
Tin	3	0.172
Tin	1	0.133

Source: Own elaboration.

The analysis of Pearson correlation coefficients between logarithmic WIG returns and lagged logarithmic commodity returns (lags of 1 to several days) indicates significant leading relationships, particularly within the group of industrial metals and crude oil. The highest and statistically significant correlations were obtained for copper, zinc, and aluminum, primarily at lags of 1-3 days, with values reaching 0.395, 0.363, and 0.342 respectively. This suggests that price changes in these commodities may signal future movements in the stock index. Brent crude oil also exhibited significant positive correlations, especially at 2-3 day lags, with a peak correlation of 0.314, reflecting the influence of the energy market on equity dynamics in Poland.

Weaker, though still statistically significant, relationships were identified for palladium, nickel, and tin, with coefficients ranging from approximately 0.13 to 0.23, indicating a moderate influence of these commodities on the WIG. By contrast, gold, silver, platinum, and lead displayed low yet statistically significant correlations, generally not exceeding 0.12, confirming their limited role as predictors of the stock index and their defensive character.

These findings suggest that industrial metals and crude oil in particular may function as leading indicators for the Polish equity market, with potential applications in forecasting models. Importantly, although the observed correlations are moderate in magnitude, they are statistically significant, underscoring the real nature of these relationships and their potential usefulness in investment analysis and in research on the linkages between commodity and equity markets.

5. Conclusion

The conducted study demonstrated that the commodity market—particularly industrial metals and crude oil—can serve as an important leading indicator for the WIG index. The analysis of contemporaneous correlations revealed strengthening linkages between selected commodities and the Polish equity market, with the highest coefficients observed for copper,

zinc, aluminum, and Brent crude oil, confirming the significance of these assets in the context of economic fundamentals and the business cycle. By contrast, precious metals such as gold and silver exhibited low and often statistically insignificant correlations, underscoring their distinct role as defensive assets.

Especially valuable insights were provided by the lagged correlation analysis, which revealed significant, albeit moderate, positive relationships between the returns of selected commodities and the WIG index, most frequently occurring at lags of 1 to 3 days. These results confirm that commodity price changes—particularly in copper and oil—may signal future trends in the stock market, creating potential opportunities for their application in forecasting models and investment strategies.

A limitation of the study remains the fact that correlation does not imply causality, and the strength of the observed relationships may also be influenced by external factors such as exchange rate fluctuations or global economic shocks. Despite these limitations, the findings make an important contribution to understanding the mechanisms of interdependence between the commodity market and the Polish stock exchange and may serve as a foundation for further research in this field.

In further research, it is advisable to apply more advanced econometric tools that make it possible to distinguish short-term speculative effects from long-term structural relationships. In particular:

- VAR (Vector Autoregression) and VECM (Vector Error Correction Model) – enable the analysis of dynamic linkages and the testing of cause-and-effect (Granger) relationships.
- GARCH, EGARCH, DCC-GARCH models – allow the assessment of volatility and the changing strength of correlations over time.
- Markov Switching Models (MSM) – make it possible to examine differences in relationships during normal and crisis periods.
- Predictive regressions and machine learning models (e.g., LASSO, Random Forest, XGBoost) – can capture nonlinear relationships and increase forecast accuracy.

Incorporating these methods will provide a more comprehensive understanding of interdependence mechanisms and enhance the practical usefulness of research for both investors and policymakers.

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AUDIT OPINION MODIFICATIONS ON THE EXAMPLE OF WARSAW STOCK EXCHANGE-LISTED COMPANIES

Ewa CHROSTOWSKA

Department of Accounting, University of Gdańsk; ewa.chrostowska@ug.edu.pl, ORCID: 0000-0001-5128-8743

Purpose: The article aims to answer the question of how many companies received modified audit opinions, the type of these modifications, the audit firms that issued these opinions, and the matters causing the modifications resulting in 'qualified opinions'.
Design/methodology/approach: The study covered companies listed on the Warsaw Stock Exchange Main Market. A total of 390 (out of 410) audit reports on 2023 annual financial statements of 390 (out of 410) companies were examined. Content analysis of independent auditors' reports was employed, with particular emphasis on the 'Opinion' and 'Basis for Opinion' sections.
Findings: Auditors modified their opinions in 4.6% of the analyzed population, exclusively in the case of smaller companies not included in the WIG20, mWIG40, and sWIG80 indices. The most common modified audit opinion, rendered in 2.8% of the population analyzed, was 'qualified opinion,' followed by 'disclaimer of opinion' in 1.8% of the population, with no incidence of 'adverse opinion.' The financial statement audits were carried out by 41 audit firms, 25% of which represented the so-called Big Four. Modified opinions were issued by 24% of the auditors. A variation in the matters causing the 'qualified opinions' in individual entities was observed, with the common factor of inability to obtain sufficient and appropriate audit evidence in 91% of these opinions.
Research limitations/implications: The study was limited to one year's content of the financial statement audit reports published by listed companies on their websites. The analysis of modification-causing matters was limited to 'qualified opinions' only. The article provides a starting point for further empirical research, including comparative studies, particularly into the matters causing other types of modified audit opinions and the narrative style used in those opinions.
Originality/value: The article partially fills the research gap in empirical studies on modified audit opinions, within the context of Polish stock exchange-listed companies' financial statements, providing a practical study of disclosures leading to the issuance of 'qualified opinions'.
Keywords: modified audit opinion, qualified opinion, adverse opinion, disclaimer of opinion.
Category of the paper: Research paper.

1. Introduction

In accordance with Poland's National Standards on Auditing (Polish: Krajowe Standardy Badania, KSB) and the International Standards on Auditing, independent auditors are tasked with formulating opinions on financial statements and clearly expressing those opinions in their audit reports. These opinions serve as a key element building the credibility of financial-statement information, particularly significant for publicly traded companies. They are perceived as a reliable source of company performance information for all stakeholders (Nurhidayah et al., 2024). A reliable assessment, based on professional judgment, contained in the opinion, is of extraordinary value to both the entity and users of the information it provides (Wielgórska-Leszczyńska, 2010).

As noted by Qiong and Rahmat (2024), "[an] audit opinion gives specific evaluation results regarding the audited financial statement, which serves to reduce information asymmetry among stakeholders […]". Furthermore, it provides a synthetic assessment of financial statement reliability that can be heeded by entity stakeholders, with its content relevant to the entity's survival (Nurhidayah et al., 2024). Modifications to the opinion can trigger significant market consequences, affecting stock valuation, investment risk perception, or capital allocation decisions, and thus an entity's ability to obtain financing. The type of opinion issued is not only of key significance, as it represents a major factor determining stakeholders' assessment of financial statement reliability and regulators' ability to monitor listed companies, but also considerably shapes the approach of listed companies to the management of matters requiring disclosure in financial statements (Qiong, Rahmat, 2024). "Qualified opinion is highly significant for building stakeholder confidence, ensuring transparency in financial reporting […]. It also contributes to continuous improvement and more informed decision making […]" (Simões, Carvalho, 2024, p. 18). This conclusion likewise applies to other modified opinions, i.e., 'adverse opinions' and 'disclaimers of opinion'.

The aim of the article is to answer the question of how many Warsaw Stock Exchange (WSE) Main Market-listed companies were issued modified auditor's opinions on their financial statements, what types of modifications were involved, which audit firms submitted the said opinions, and what matters prompted the modifications resulting in qualified opinions. These considerations are of vital relevance, as investors and stakeholders rely on auditors' opinions in forming judgments regarding companies, and utilize these opinions as substantial guidance in their decision-making (Qiong, Rahmat, 2024). To accomplish the article's objective, an analysis of independent auditors' reports on the 2023 annual financial statements of WSE Main Market-listed companies was conducted. The content analysis of auditors' reports was carried out in a breakdown into: the largest, medium-sized, and small entities included in the WIG20, mWIG40, and sWIG80 indices, respectively, alongside other entities (GPW Benchmark Indices, 2023). Examined was whether independent auditors issued modified

opinions or not, while identifying the entities that issued these opinions. For modified opinions, the type of modification was determined. Additionally, analyzed were the disclosures of matters to which the reservations referred. The study covered 390 (out of 410) independent auditors' reports on the audit of financial statements of 390 companies (out of 410 companies). The study was divided into two stages. The first stage of the empirical research was aimed at identifying which and how many companies received modified opinions on their financial statements, which auditors issued these opinions, and what types of modified opinions were involved in individual cases. The second stage was aimed at determining what matters caused the modifications resulting the qualified opinions issued by the auditors.

The following research methods were employed in the study: a review of legal regulations, analysis of source literature, in-depth analysis of independent audit reports on company financial statements, followed by logical induction and synthesis to refine the research conclusions.

Empirical research on auditors' opinions, with respect to financial statements of WSE-listed companies, is relatively scarce. The majority of empirical studies in the field of audit opinions draw upon developed capital markets, including the US market. As Lu (2020) notes, numerous factors affect auditors' opinions, and studies of these diverse factors are bound to generate different conclusions, due to varying national conditions and research perspectives. Therefore, the Author's intention in the present study is to contribute to partially filling the research gap in current empirical research on modified opinions, in the context of financial statements of Polish stock exchange-listed companies. The article also provides a practical study of disclosures concerning the matters triggering the issuance of qualified opinions. The results obtained in the study may serve as a starting point for further analysis.

The article is divided into two parts: a theoretical part presenting the subject of independent auditor's opinion, with particular emphasis on modified opinion, against the backdrop of legal regulations and publications by selected authors, as well as an empirical part covering the methodology and two stages of the study. It concludes with a summary of the main findings, indicating the limitations and directions for possible future research.

2. Review of the Literature and Legal Regulations

In accordance with Poland's National Standards on Auditing (NSA) and the International Standards on Auditing (ISA), the purpose of an audit is to increase the level of intended users' confidence in the financial statement, achieved by the independent auditor expressing an opinion on whether it has been prepared, in all material respects, in conformity with the applicable financial reporting framework (KSB 200 in the wording of ISA 200 "Overall Objectives of the Independent Auditor and the Conduct of an Audit in Accordance with

International Standards on Auditing", para. 3). A similar position has been taken by Ruban and Hațegan (2022, p. 679), who concluded that "the auditors' reporting of opinions based on a high level of professionalism contributes to increasing stakeholders' confidence in the company's financial statements and activities". The literature on the subject presents the view that an independent auditor's opinion is of high significance to the capital market and shareholders, serving "as a powerful monitor tool [that] could influence the decision of investors and other stakeholders" (Tian, Xin, 2017, p. 266).

In light of the NSA and ISA, the objective of the auditor is both to formulate an opinion on the financial statement based on an assessment of the conclusions drawn from the audit evidence obtained and clearly express that opinion in a written report, (KSB 700 (Z) in the wording of ISA 700 (Revised) "Forming an Opinion and Reporting on Financial Statements", para. 6). According to paragraph 16 of the National Standard on Auditing 700 (Z), if the auditor concludes that the financial statement has been prepared, in all material respects, in conformity with the applicable financial reporting framework, he/she expresses an unmodified opinion. If, however, the auditor concludes that, based on the audit evidence obtained, the financial statement, as a whole, contains material misstatements, or is unable to obtain sufficient and appropriate audit evidence to conclude that the financial statement, as a whole, is free of material misstatements, he/she modifies the opinion (KSB 700 (Z), para. 17).

Modification of opinions has been regulated by NSA 705 (Z) in the wording of ISA 705 (Revised) "Modifications to the Opinion in the Independent Auditor's Report". This standard defines three types of modified opinions: 'qualified opinion', 'adverse opinion' and 'disclaimer of opinion'. The types of opinions, categorized into modified and unmodified, are presented in Figure 1.

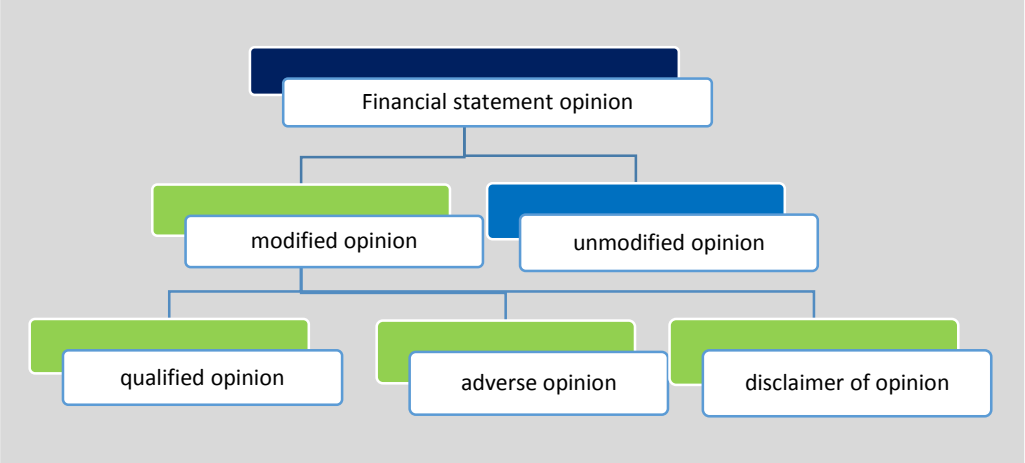


Figure 1. Types of independent auditor's opinions on financial statements.

Source: Own elaboration based on National Standard on Auditing 705.

According to the provisions of NSA 705 (Z), the auditor issues an appropriate modified opinion on the financial statement depending on specific circumstances (paras. 7-10):

- a ‘qualified opinion’ – when misstatements, individually or in aggregate, are material but not pervasive (based on sufficient and appropriate audit evidence), or when the possible impact of any undetected misstatements could result in material but not pervasive consequences (inability to obtain sufficient and appropriate audit evidence);
- an ‘adverse opinion’ – when misstatements, individually or in aggregate, are both material and pervasive (based on sufficient and appropriate audit evidence);
- a ‘disclaimer of opinion’ – when the possible impact of any undetected misstatements could entail both material and pervasive consequences (inability to obtain sufficient appropriate audit evidence), or when, in the presence of multiple uncertainties, expression of an opinion is precluded due to the potential interaction of these uncertainties and the possible cumulative effect thereof (despite obtaining sufficient and appropriate audit evidence for each of these uncertainties).

The standard also regulates the form and content of an auditor's report in the event of a modified opinion. The auditor adds the words ‘qualified’, ‘adverse’ or ‘disclaimer of opinion’ to the section headers ‘Opinion’ and ‘Basis for Opinion’, depending on the type of modification. Detailed regulations regarding the content of the ‘Qualified Opinion,’ ‘Adverse Opinion’ and ‘Disclaimer of Opinion’ sections are contained in paragraphs 17, 18 and 19 of NSA 705 (Z), respectively. The required content of the ‘Basis for Opinion’ comprises, inter alia: a description of the matter causing the modification, a description and quantification of the financial impact with respect to the misstatements (including quantitative disclosures), an explanation of how the qualitative disclosures have been misstated, and, in the absence of disclosures, inclusion and description of the missing information. In the case of both an ‘adverse opinion’ and a ‘disclaimer of opinion,’ the standard requires the auditor to describe the reasons and effects of any other matters of which he/she is aware, necessitating the modification of the opinion.

Furthermore, according to the NSA and ISA, the ‘Emphasis of Matter’ paragraph featured in audit reports refers to matters “of such importance that it is fundamental to users’ understanding of the financial statements”, while the ‘Other Matter’ paragraph references matters that are “relevant to users’ understanding of the audit, the auditor’s responsibilities or the auditor’s report (KSB 706 (Z) in the wording of ISA 706 (Revised) “Emphasis of Matter Paragraphs and Other Matter Paragraphs in the Independent Auditor's Report”, para. 7). Despite the importance of these paragraphs, opinions containing such, yet for reasons other than those indicated in the respective paragraphs not classified as modified opinions, are considered unmodified opinions under the NSA and ISA.

As an additional note, worth mentioning is that WSE-listed companies are required to present the management board's position along with the supervisory board's opinion on the auditing firm's opinion in their report, in the event of a modification of the opinion. The report should specify the impact of the modification on the financial statement, both quantitative and qualitative, along with an assessment of the significance of this impact (Regulation of the Minister of Finance on current and periodical information published by issuers of securities and on conditions under which information required by legal regulations of a third country may be recognized as equivalent, 2018, 2025).

In the literature on the subject, audit opinion-related issues have been studied by numerous authors who have analyzed these aspects from various perspectives. This topic has been explored both through literature studies and empirical research. Scholars have reviewed the literature on, inter alia, auditor's opinion (Tian, Xin, 2017; Lu, 2020; Nurhidayah et al., 2024) and modified opinions (Matonti et al., 2024; Tommasetti et al., 2018; Simões, Carvalho, 2024). Researchers also delved into the impact of various specific factors on the likelihood of a modified opinion issuance (Habib, 2013; Moazedi, Khansalar, 2016; Tommasetti et al., 2018; Ruban, Haţegan, 2022; Matonti et al., 2024; Qiong, Rahmat, 2024; Simões, Carvalho, 2024), as well as studied the market response to different types of audit opinions (Tahinakis, Samarinas, 2016; Cipriano et al., 2016 ;Tian, Xin, 2017; Carp, Georgescu, 2019; Moţoc, 2022), including exploration of the economic consequences from the textual information contained in audit opinions (Zhao, Lin, 2015). Matonti et al. (2024) analyzed the relationship between intellectual capital and the occurrence of a modified audit opinion, based on a study of publicly traded companies in Greece, Italy, Spain, and Portugal. They furthermore reviewed the literature on factors influencing the occurrence of modified opinions, using the classification applied in an earlier meta-analysis by Habib (2013), in which two broad categories of determinants were distinguished: auditor- and audit-specific variables, as well as firm-specific variables. Overall, the authors concluded that the existing published studies have provided empirical evidence that the factors described in their literature review may contribute to the likelihood of a modified audit opinion (see Matonti et al., 2024). The literature review they presented referenced, inter alia, the aforementioned meta-analysis conducted by Habib (2013), covering 73 studies published worldwide between 1982 and 2011. Simões and Carvalho (2024) conducted a comparative analysis of the main conclusions from studies on the determinants of qualified/modified auditor's opinion issuance in the privately owned and state-owned sectors. The results are presented in a summary table containing a list of the variables studied, with indication of the derived direction of the impact thereof on the auditor's opinion (see Simões, Carvalho, 2024, pp. 6-7).

As part of empirical research on Polish listed companies, identification of the determinants of WSE-listed companies' receipt of opinions other than unqualified, and determination of the directions of the impact thereof on the probability of receiving such opinions, were addressed by Włodarczyk and Białek-Jaworska (2018). Conclusions concerning the audit services market were also published by Grant Thornton - an entity authorized to audit financial statements - in a report entitled "Audyt spółek giełdowych w Polsce" (eng. Audit of listed companies in Poland) (2025). This analysis, in accordance with the study's subtitle, focused on the market of independent auditors who audit the financial statements of Warsaw Stock Exchange-listed companies. The report is based on a limited number of observations, however, due to the lack of available data at the time of the analysis, which raises doubts as to the validity of comparing its results with those of the present study. Moreover, the results presented in the study on the opinions issued by independent auditors are difficult to comment on due to the lack of a detailed description of the research methodology underlying the conclusions and the unclear, according to the author, classification of opinions applied in the report. Unlike the present publication, the authors of the aforementioned report failed to address the matters that prompted the modifications resulting in 'qualified opinions.' Analysis of independent auditors' opinions on the financial statements of listed companies was also addressed in a work by Wielgórska-Leszczyńska (2008), covering 1407 financial statements for the years 2001-2006.

As noted by Lu (2020, pp. 34-35), "[a]t present, there are two ways to divide audit opinion in the research of audit opinion […]. [O]ne is to take standard unqualified audit opinion as standard audit opinion, the other is non-standard audit opinion. This is also the method adopted by most of the literature […]. The second is to define the type of unqualified audit opinion as the standard unqualified audit opinion and the unqualified opinion with emphasis, and the rest as the non-standard audit opinion". The inconsistency in the categorization of audit opinions has also been called attention to by Qiong and Rahmat (see 2024), as well as Simões and Carvalho (see 2024, pp. 3-4). The diversity of the classifications adopted by researchers may pose difficulties in study comparisons. In the present article, the subject of empirical research is modified opinions, as defined in the NSA and ISA. Accordingly, opinions from 'Emphasis of Matter' or 'Other Matter' paragraphs, insofar as they have not been classified as modified opinions for reasons other than those indicated in these paragraphs, constitute unmodified opinions, and are presented as such in the results of the empirical study.

3. Empirical Research Methodology

The results presented in the article follow from the content analysis of independent auditors' reports on the financial statements of WSE Main Market-listed companies. Analyzed were the audit reports on the annual financial statements for 2023 and, in cases of a fiscal year not corresponding to the calendar year, for the fiscal year beginning in 2023 and ending in 2024.

The analysis concerned in particular the content of two sections of the auditors' reports on the audit of company financial statements: the ‘Opinion’ section and the ‘Basis for Opinion’ section. In cases of consolidated financial statements, audit reports on consolidated financial statements, and audit reports on separate financial statements otherwise, were analyzed.

Out of 410 entities listed on the Main Market of the Warsaw Stock Exchange as of March 6, 2025, 390 were included in the analysis of auditors' reports on the audit of financial statements. The remaining 20 entities were excluded from the analysis:

- 2 entities debuting on the Warsaw Stock Exchange in 2024 and 2025,
- 18 companies, due to non-publication of financial statement audit reports on company websites.

In the first stage of the study, analyzed was whether a modified auditor’s opinion was issued or not, while identifying the entity conducting the financial statement audit. In cases of a modified opinion, the type of opinion was analyzed, i.e., whether the opinion consisted of a ‘Qualified Opinion’, an ‘Adverse Opinion’, or a ‘Disclaimer of Opinion’ on the financial statement. The study was conducted by dividing the companies into four groups, taking their stock exchange index qualification into account: WIG20 - comprising the 20 largest entities, mWIG40 - comprising 40 medium-sized entities, sWIG80 - consisting of 80 small companies, and a group of other entities not included in the above-specified indices. In this step, the content of audit reports was analyzed, with particular emphasis on the header and the text of the ‘Opinion’ section.

In the second stage, reports with ‘qualified opinions’ issued by the auditors were examined, analyzing the matters that prompted the modifications resulting in the issuance of such opinions. For this purpose, content analysis of audit reports was employed, with particular focus on the ‘Opinion’ and ‘Basis for Opinion’ sections.

A total of 390 auditor reports on the audit of 2023 financial statements of 390 companies were examined:

- 20 companies comprising the WIG20 index,
- 39 entities included in the mWIG40 index,
- 79 entities included in the sWIG80 index,
- 252 companies not included in the above-listed indices.

The research material was collected utilizing the Warsaw Stock Exchange website and company websites.

4. Research Results

In the first stage of the study, identifying whether or not the auditors issued modified opinions, the analysis of the audit report content, with particular focus on the "Opinion" sections, revealed that out of the 390 companies examined, modified opinions on financial statements were issued by the auditors in 18 cases. In regard to the remaining companies, the auditors concluded that no opinion modification was required in the audit reports (Table 1).

Table 1.
Confirmation of the occurrence of modifications to independent auditors' opinions on the audited companies' financial statements

No.	Occurrence of modifications to auditor's opinion	Number of companies
1.	Yes	18
2.	No	372
3.	Total	390

Source: Own elaboration based on independent auditors' reports on the audit of companies' financial statements.

The financial statements of all 390 companies were audited by auditors representing 41 entities authorized to audit financial statements. In 94 companies, the audits were conducted by companies from the so-called Big Four. One report was audited by two auditing companies. The number of opinions, in distribution by the entities that audited the financial statements, is presented graphically (Figure 2). The audit firms that audited fewer than four financial statements are grouped in the chart under the item 'other,' whereas the legend data is ordered by the number of opinions issued, starting with the entity which issued the most.

Modified opinions were issued by auditors from 10 audit firms, i.e., 24% of the entities conducting the audits. Figure 3 shows the number of modified opinions in distribution by entities that audited the financial statements.

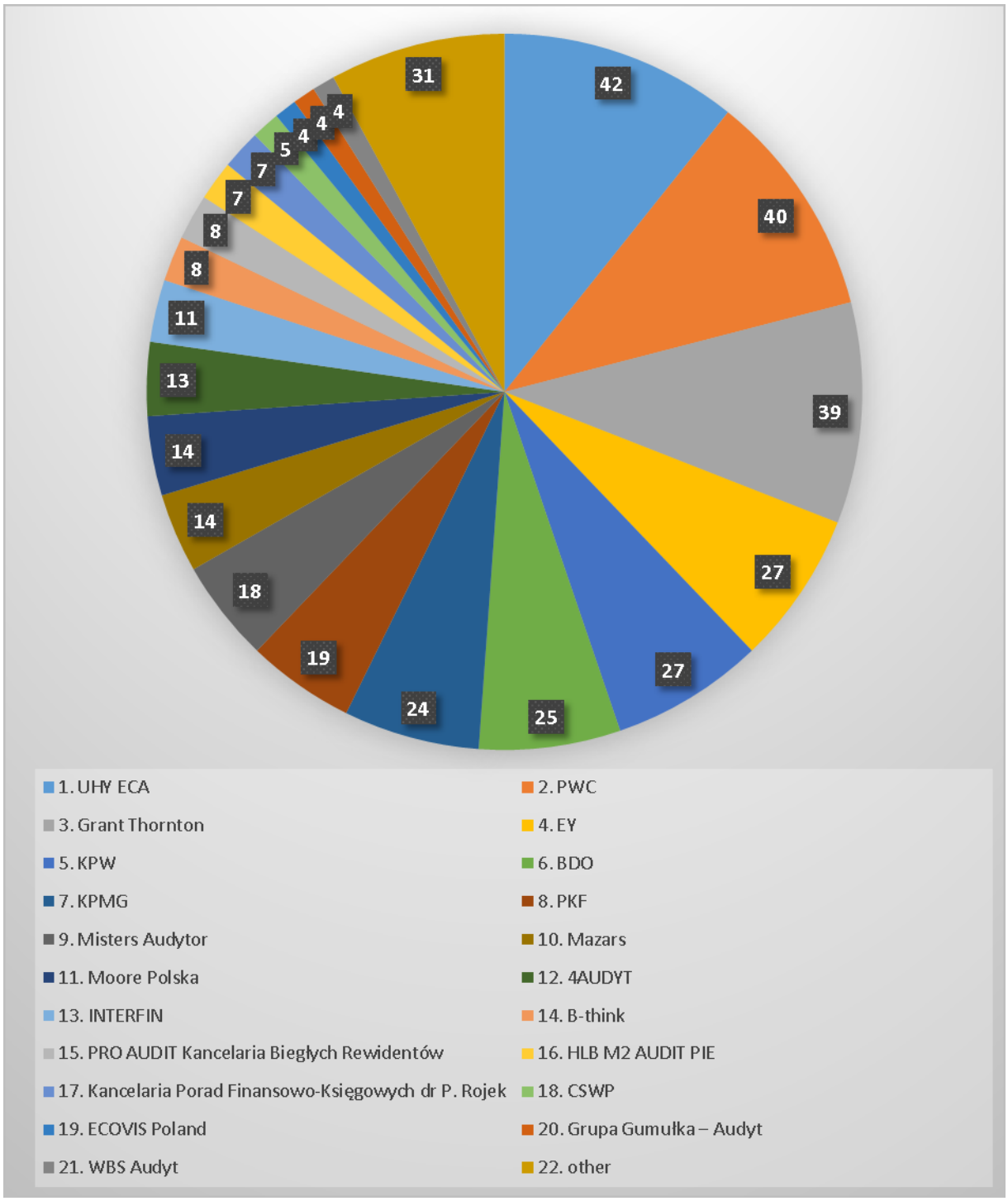


Figure 2. Number of opinions - in distribution by audit firms conducting the financial statement audits.

Source: Own elaboration based on independent auditors' reports on the audit of companies' financial statements.

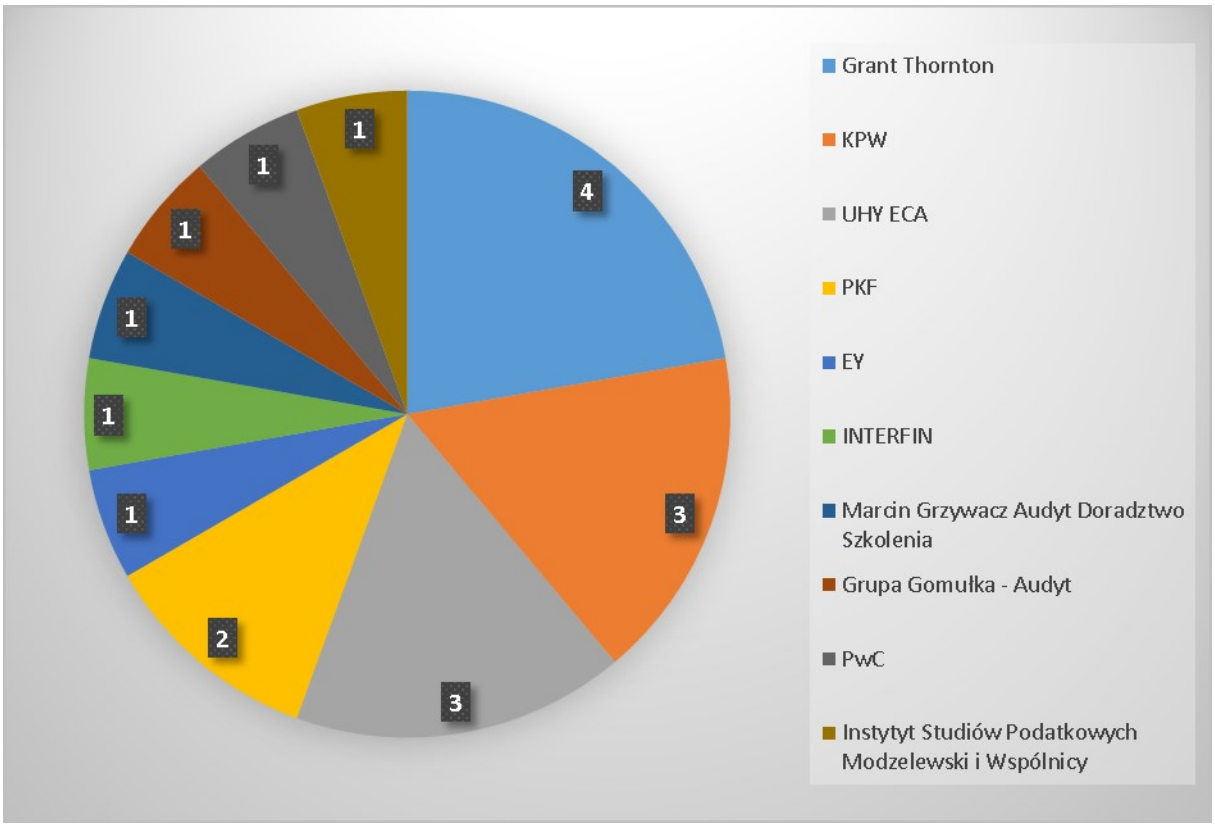


Figure 3. Number of modified opinions - in distribution by audit firms conducting the audit of financial statements.

Source: Own elaboration based on independent auditors' reports on the audit of companies' financial statements.

The share of modified opinions in the total number of opinions issued by a given auditing firm that issued more than 10 opinions is presented in Table 2.

Table 2.
Share of modified opinions in the number of opinions issued by a given auditing firm – entities with more than 10 opinions issued

Name of auditing firm	UHY ECA	PWC	Grant Thornton	EY	KPW	BDO	KPMG	PKF	Misters Audytor	Mazars	Moore Polska	4AUDYT	INTERFIN
Percentage share of modified opinions in the number of opinions issued by the audit firm	7.1	2.5	10.3	3.7	11.1	0	0	10.5	0	0	0	0	9.1
Number of modified and unmodified opinions issued by the audit firm	42	40	39	27	27	25	24	19	18	14	14	13	11
Number of modified opinions issued by the audit firm	3	1	4	1	3	0	0	2	0	0	0	0	1

Note: The data is sorted from left to right, according to the number of opinions issued, starting with the entity that issued the most opinions.

Source: Own elaboration based on independent auditors' reports on the audit of companies' financial statements.

Based on the analysis, no modified auditor's opinions have been identified in the case of financial statements of the WIG20, mWIG40, and sWIG80 stock-index companies. Modified opinions were found exclusively in relation to the financial statements of other entities not included in the above-listed stock indices. Furthermore, the results of the presented study do not incorporate 'qualified opinions,' in cases of companies which, after receiving and then publishing their financial statements inclusive of such opinions, corrected those statements and republished them with a subsequent audit report replacing the previous one, containing no modification of the opinion.

The empirical analysis resulted in a three-group classification of modified opinions based on the type of modification: 'qualified opinions,' 'adverse opinions,' and 'disclaimers of opinion' on financial statements, as presented in Table 3.

Table 3.
Modifications to independent auditors' opinions on the financial statements of audited companies, in distribution by type of modification

No.	Type of modification to auditor's opinion on financial statement	Number of companies
1.	Qualified opinion	11
2.	Adverse opinion	0
3.	Disclaimer of opinion	7
4.	Total	18

Source: Own elaboration based on independent auditors' reports on the audit of companies' financial statements.

Table 2 shows that the most prevalent modified opinion was a 'qualified opinion,' with no instances of an 'adverse opinion' issued for any of the companies. The type of opinion modification in the respective companies is presented in Table 4.

Table 4.
Types of modification to independent auditors' opinions on financial statements in individual companies

Type of modification to auditor's opinion on financial statement	Company Name																	
	AB NOVATURAS	ADIUVO INVESTMENTS	AIRWAY MEDIX	BALTIC BRIDGE	CDRL	CFI HOLDING	DELKO	EC BĘDZIN	EKO EXPORT	ESOTIQ & HENDERSON	EUROPEJSKIE CENTRUM ODSZKODOWAŃ	GI GROUP POLAND	KERNEL HOLDING	KSG AGRO	MANYDEV STUDIO SE	PBG	RAFAKO	TOWER INVESTMENTS
Qualified opinion	1	1	1	0	1	0	1	0	0	1	0	1	1	1	1	0	0	1
Adverse opinion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Disclaimer of opinion	0	0	0	1	0	1	0	1	1	0	1	0	0	0	0	1	1	0

Note: (1) confirms the occurrence of a given type of modification, (0) indicates the absence of a given type of modification.

Source: Own elaboration based on independent auditors' reports on the audit of companies' financial statements.

In the second stage, auditors' reports with ‘qualified opinions’ were examined. Analysis of the content thereof, with particular focus on the ‘Opinion’ and ‘Basis for Opinion’ sections, enabled identification of the matters that prompted the modifications resulting in the issuance of qualified opinions.

Out of 11 ‘qualified opinions’, in 10 the auditors stated that the modification resulted from the inability to obtain sufficient and appropriate audit evidence. The wordings “except for the possible effect of the matter(s)” (6 audit reports), “za wyjątkiem skutków sprawy” (eng. except for the effects of the matter) (4 audit reports) were used in the ‘Opinion’ sections, in reference to the matters described in the ‘Basis for Qualified Opinion’ sections. In the case of one audit report, the ‘Opinion’ section did not include any words referring to the section justifying the ‘qualified opinion’. Due to the variation in the reasons for issuing a ‘qualified opinion’, the matters to which the qualifications applied are presented below in a grouping by company and the corresponding audit reports.

In the ‘Basis for Qualified Opinion’ section of the first audit report, the auditor singled out prepayments to suppliers and trade payables, relative to the group’s and company’s data. They identified significant differences in the sample of prepayment balance statements, which showed lower amounts than those presented in the financial statement. Moreover, no balance statements were received for the indicated prepayment amounts and trade payables. The auditor was unable to obtain sufficient and appropriate audit evidence regarding the impact of these matters, if any, on the current year, and comparative data on the prepayment balances and trade payables in the statement of financial position, including the related impact of adjustments that may be required, relative to statements of comprehensive income, changes in equity, and cash flows for the current period, or comparative financial information.

In the second audit report, the justification for the issuance of a ‘qualified opinion’ mentioned the amount of surplus from the sale of shares above their nominal value, presented by the capital group, and the fact that, in the comparative data for the previous year, the parent company consolidated a subsidiary, over which it lost control during the year under review. The auditor did not express an opinion on the completeness and accuracy of the disclosures regarding both of these matters and the possible impact on other elements of the financial statement, as they did not obtain adequate and sufficient audit evidence confirming the aforementioned part of equity and the subsidiary's financial data for the year under review and the preceding year.

In the case of the third company, the ‘qualified opinion’ referred to a liability arising from a bond-secured loan. The auditor did not, however, obtain adequate and sufficient audit evidence confirming the collateral and contingent liabilities in connection with this loan. Neither did they obtain audit evidence of information regarding possible financial instruments in the accounts maintained by the bank. They therefore did not express an opinion on the completeness and accuracy of the additional information in this regard, nor on the possible impact on other elements of the financial statement.

In the fourth audit report, the justification for issuing the ‘qualified opinion’ stated that the management board had recognized the effects of the actual loss of control over the Belarusian company in the consolidated financial statement, using the most recent available data for the three quarters of the year under review, but the data had not been audited at the end of the third quarter. The auditor was unable to obtain adequate and sufficient audit evidence confirming that the valuation of the assets and liabilities held by the company over which control was lost of the date of the loss of control, and the company’s revenues and costs up to the date of the loss of control, required no adjustments, and thus that the capital group's result on the loss of control had been determined correctly. A possible adjustment would not affect the capital group’s consolidated net result.

In the fifth audit report, the auditor based his ‘qualified opinion’ on the inability to confirm whether the company’s goodwill presented as of the last day of the audited year in the consolidated financial statement was disclosed in the correct amount. They did not obtain sufficient audit evidence to confirm the acquirer's valuation of identifiable acquired assets and assumed liabilities at their fair value as of the acquisition date.

In the justification for issuing a ‘qualified opinion’ of the sixth audit report, the auditor noted that the company had failed to measure the shares of its subsidiary and the receivables from that company in accordance with IAS 36, and had neglected to create provisions for retirement benefits in accordance with IAS 19. As a result, other financial assets as well as trade receivables were overstated, provisions were understated, and consequently, the net financial result was overstated. The auditor provided the amounts by which the above items were understated and overstated.

In the case of the seventh audit report, the auditor concluded that a ‘qualified opinion’ had already been issued for the previous year. They stated that the consolidated financial statement for 2020 accounted for the effects of the loss of control over one company and its capital group, using the group's latest available data for the first three quarters of 2020, disclosing the equity method adopted to measure its shares in subsequent periods. The financial results of the said group for Q4 2020, 2021, and the period from January 1, 2022, to the date of sale of the aforementioned company's shares on January 19, 2022, were not included in the Capital Group's financial results, due to non-receipt of data from the aforementioned group. The group's data for the last day of the third quarter of 2020 were not audited. The auditor was unable to obtain appropriate and sufficient evidence confirming that the valuation of the group's assets and liabilities, as of that date, required no adjustments. Due to the lack of data, they were not able to estimate the possible impact on the comparative data in the consolidated financial statement for the current financial year, nor the Capital Group's share in the results of this group for the fourth quarter of 2020, 2021, and the period from January 1, 2022, to the date of sale of the aforementioned company's shares on January 19, 2022.

In the eighth audit report, the auditor stated in the 'Basis for Qualified Opinion' section that the group had sold all its crypto assets in the previous financial year, disclosing the loss on the sale and citing the amount of the loss. At that time, no sufficient appropriate evidence was obtained to verify the opening balance of the crypto assets at the beginning of the previous year, and the transactions on crypto assets during the previous year. It was therefore not possible to determine whether adjustments to the crypto asset balances at the beginning of the previous year or adjustments to the losses on transactions in crypto assets in the previous year were necessary. The audit report for the year preceding the year under review contained reservations on this matter. The opinion for the current financial year likewise contains a qualification due to the possible impact of this matter on the comparability of the current-period data with the corresponding data.

In the ninth audit report, the auditor referred to several matters in the justification for issuing a 'qualified opinion.' The carrying amount of property, plant, and equipment at the end of the period covered by the audit included an amount attributable to prior-year adjustments that was not assigned to any specific property, plant, and equipment items. The auditor was unable to obtain sufficient appropriate audit evidence as to whether this accounting entry was justified, and was not able to determine the impact of this matter on the financial statement. This resulted in a 'qualified opinion' also for the previous financial year. Determination of whether year-end profit and retained earnings needed to be adjusted was likewise not possible. Moreover, the management board was unable to provide calculations supporting the recognized right-of-use assets and related lease liabilities. The auditor disclosed the amounts of assets from the right of use of the leased plots and the lease liabilities recognized as of the last day of the year under review, as well as the depreciation amounts of the right-of-use assets and lease interest, the accuracy of which he was unable to confirm. The management board also retrospectively adjusted the inventory amounts as of the last day preceding the audited year, thereby increasing the opening inventory for the year under review. The board made no adjustments to the amounts recognized in the financial statement, however. The auditor was not able to verify the correctness of the inventory adjustment in estimating its maximum value. Nevertheless, they were unable to determine whether any adjustments to the cost of sales were necessary.

In the case of the tenth company, the 'basis for qualified opinion' included an indication that the auditor did not obtain adequate and sufficient audit evidence confirming the value of cash at the last day of the year under review, nor any audit evidence regarding information on possible financial instruments in the accounts maintained by the bank. Accordingly, they did not express any opinion on the completeness and accuracy of the additional information in this regard, and the possible impact on other elements of the financial statement.

The auditor's justification for issuing a 'qualified opinion' in the case of the eleventh company referred to the amount of the company's goodwill presented for the last day of the audited year. As of the date of the audit report issuance, no sufficient and appropriate audit evidence had been gathered to confirm the value of the item. The impairment tests received

were found to be insufficient. The auditor also stated that this area may be subject to significant value distortion.

5. Conclusion

The objective in the present article was to determine how many Warsaw Stock Exchange Main Market-listed companies received modified auditor's opinions in the independent audit reports on their financial statements, the types of modifications made, the auditing firms that effected such modifications, and the matters covered by the qualifications in the opinions issued by the auditors. This objective was achieved by analyzing the content of the auditors' reports on the audit of the 2023 annual financial statements of WSE Main Market-listed companies. The research resulted in a practical study of disclosures in the modified opinions issued during the period under analysis, with particular emphasis on 'qualified opinions.'

The analysis of empirical data revealed that out of the 390 companies under study, in 18 cases the auditors modified their opinions in the independent audit reports on the companies' financial statements. Modified opinions thus accounted for 4.6% of the opinions covered by the analysis, which indicates that, in the auditors' judgment, 95.4% of the financial statements in the studied population required no modification of the opinion. The modifications only applied to the financial statements of smaller companies, i.e., not included in the WIG20, mWIG40 and sWIG80 indices, occurring exclusively in the case of the group of other entities not included in the above-named indices. The results of the study show that the most frequently issued modified opinion was 'qualified opinion', identified in the case of 11 entities, i.e., 2.8% of the population under study. 'Disclaimers of opinion' were issued by the auditors in the case of 7 audit reports, i.e., 1.8% of the opinions analyzed. No 'adverse opinions' were found. Qualified opinions' thus accounted for 61.1% and 'disclaimers of opinion' for 38.9% of the modified opinions covered by the study. Content analysis of the auditors' reports found that the financial statements of 390 companies were audited by 41 audit firms, including 94 companies audited by the Big Four, which reviewed 24% of the reports. Modified opinions were issued by 10 entities authorized to audit financial statements, i.e., 24% of the entities conducting the audits. In the group of audit firms which issued more than 10 opinions, the share of modified opinions in the number of opinions issued by a given entity ranged from 0% to 11.1%, while in the group of the so-called Big Four firms the range varied from 0% to 3.7%. Furthermore, the results of the study indicate a diversity of the matters causing the modifications resulting in the issuance of 'qualified opinions'. In the case of 10 out of the 11 companies, representing 91% of the 'qualified opinions', the auditors concluded that sufficient and appropriate audit evidence could not be obtained. Recurring matters causing modifications in the form of 'qualified opinions' involved matters concerning the recognition

of effects of a loss of control over a company in the financial statements of three companies, and the inability to confirm the amount of goodwill value in the case of two companies. Other matters justifying the issuance of a ‘qualified opinion’ varied among individual entities. Moreover, in the case of three entities, the ‘basis for qualified opinion’ included information that the audit report for the year preceding the year under review likewise contained a qualification regarding the very same matter as in the audited year.

One interesting benchmark in time, in the Author’s assessment, seems to lie in a comparison of the results obtained with the findings of the study on auditors' opinions on 2001-2006 financial statements published under the editorship of Wielgórska-Leszczyńska (2008). According to the results of that analysis, modified opinions at the time accounted for 10.87% of the opinions examined, while 89.13% of the financial statements required no modifications to the opinion. In parallel, 10.66% of the analyzed opinions constituted ‘qualified opinions’, and 0.21% comprised ‘disclaimers of opinion’, while audit firms from the so-called Big Five and subsequently from the Big Four examined 31% of the reports (Wielgórska-Leszczyńska, 2008, pp. 88-89, 102).

Concluding, it should be noted that the present study carries several limitations. The findings presented in the article apply only to the audit reports included in the analysis. Firstly, the analysis covered exclusively the content of Warsaw Stock Exchange-listed companies' financial statement audit reports. Secondly, the analysis was limited to the audit reports for 2023 available on the Warsaw Stock Exchange and company websites. Thirdly, due to editorial limitations, cases resulting in an opinion other than a ‘qualified opinion’ were not examined in detail. Furthermore, as mentioned earlier, the literature on the subject shows “no consensus regarding the concept and delimitation of the scope of qualified and modified opinion” (Simões, Carvalho, 2024, p. 4), and the inconsistency in the categorization of audit opinions (Qiong, Rahmat, 2024; Simões, Carvalho, 2024) may limit the comparability of studies, including the present study. The method of audit opinion classification employed in the article has been therefore defined precisely. Opinions contained in the ‘Emphasis of Matter’ or ‘Other Matter’ paragraphs, insofar as they were not classified as modified opinions for reasons other than those indicated in these paragraphs, were classified as unmodified opinions and presented as such in the results of the empirical study. Worth noting is also that the Author is nonetheless aware these paragraphs carry content relevant and even fundamental to the understanding of the financial statements, and may serve as a subject for further empirical research. Important to mention is likewise that the article employs only the content analysis method of independent auditors' reports. This limited the study to the perspective of specific auditors issuing modified opinions on specific financial statements. Neither the market's reaction nor the company management boards' or other auditors' responses to these opinions were examined, which could involve other research methods, including surveys.

The article may provide a starting point for further empirical research, including comparative studies covering subsequent periods. The Author plans to conduct research on matters underlying such modification as the issuance of a 'disclaimer of opinion,' which will constitute a continuation of the considerations raised in the present article. Another area of interesting analysis seems to lie in the narrative style used by auditors when formulating opinions. This has been confirmed, inter alia, by Zhano and Lin, who noted that "[…] investors may differentially treat modified opinions by textual tone, suggesting that text conveys additional information apart from that conveyed by figures, which makes the information content of audit opinions more than just a dichotomy of [0&1]" (2015, p. 42). In the Author's opinion, the analysis conducted in the present study allows for the formulation of a hypothesis worth testing in future empirical research, stating that impression management techniques are also used by auditors in modified opinions on financial statements, including those published by Warsaw Stock Exchange-listed companies.

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SOCIAL MEDIA IN MANUFACTURING COMPANIES – A CASE STUDY

Piotr R. CIEBIADA

Lodz University of Technology; piotr.ciebiada@dokt.p.lodz.pl, ORCID: 0009-0008-9436-3641

Purpose: The paper evaluates the effectiveness of social media communication in selected manufacturing companies from the Łódź Voivodeship, Poland. It examines platform choice, efficiency indicators, the role of sector-specific characteristics, and dominant content strategies.
Design/methodology/approach: A case study approach was applied to three enterprises from the food, cosmetics, and heavy industry sectors. Data were collected through semi-structured interviews with managers, observation of official profiles, and analysis of public and partial non-public metrics. A mixed-methods strategy integrated qualitative content analysis with quantitative indicators such as engagement rates and average interactions per post. Triangulation of sources, including advertising libraries and platform dashboards, ensured validity.
Findings: Results show sectoral variation. Company A emphasized educational and utilitarian content, amplified by a viral effect. Company B adopted visual storytelling and influencer promotion. Company C concentrated on LinkedIn to build credibility and reputation. Despite differences, all firms considered social media indispensable for visibility and competitiveness. Engagement proved uneven, often concentrated around single high-performing posts or seasonal campaigns, reflecting both potential and volatility of digital communication.
Research limitations/implications: The study was restricted to publicly accessible data and partial platform insights, without financial indicators such as ROI. Its cross-sectional scope limited the ability to assess long-term outcomes. Future research should include longitudinal studies, financial measures, and broader comparative contexts.
Practical implications: The research suggests that systematic, tailored strategies across platforms are more effective than reliance on viral success. SMEs should invest in analytical tools and digital competences to strengthen competitiveness and market presence.
Social implications: Social media was shown to enhance transparency, customer engagement, and credibility. It supports community building through educational content and reinforces corporate social responsibility, contributing to sustainable practices and stakeholder trust.
Originality/value: The paper fills a gap by analyzing manufacturing firms in a regional Polish context, rarely examined in prior research. Its novelty lies in combining qualitative and quantitative approaches, comparing three sectors, and providing practical recommendations for optimizing digital strategies.
Keywords: Social media, Manufacturing companies, Digital marketing, Case study.
Category of the paper: Research paper.

1. Introduction

The development of digital technologies over the past two decades has revolutionized the functioning of modern enterprises, imparting a new dimension to their activities in communication, marketing, and customer relationship management (Zachlod et al., 2022). Social media, one of the most significant innovations of the digital era, has become an essential tool in the digital transformation process of organizations (Boyd, Ellison, 2007). It has enabled not only reaching a broad audience but also conducting real-time, two-way communication. Platforms such as Facebook, Instagram, LinkedIn, TikTok, and YouTube offer companies a wide spectrum of opportunities-from brand image building (Luo et al., 2024) to analyzing consumer preferences (Karpińska-Krakowiak, 2016), as well as engaging customers in corporate activities through interactive, personalized, innovative (Siuda, 2018), and nostalgia-evoking content (Gręboszc-Krawczyk et al., 2021). Consequently, social media has become an indispensable component of corporate marketing strategies (Gao et al., 2018).

Despite the awareness of social media's role in managing modern organizations, scientific literature still lacks studies focusing on its application in regional contexts, particularly in Poland. Most existing research concentrates either on analyzing social media in administrative units (Kotnis, 2023; Kowalik, 2021; Krawczyk, 2022; Woźniakowski, 2023) or global corporations and national trends(Ilieva & McPhearson, 2018), often neglecting the specificity of local enterprises, which frequently operate under different market conditions. Furthermore, small and medium-sized enterprises (SMEs) often face constraints in their social media activities due to limited resources-both financial and human-further complicating effective utilization (Braojos-Gomez et al., 2015). The Łódź Voivodeship, characterized by a diverse economic structure, represents an intriguing research area for studying the use of social media by local businesses (Cudny et al., 2020). As one of Poland's key industrial and commercial hubs, the region includes both long-established companies and modern tech enterprises. The challenges of the 21st century, such as globalization, changing consumer preferences, and the development of new technologies, compel local businesses to seek innovative solutions in marketing communication (Stasiak, 2016; Zasina, 2018).

Social media, due to its unique characteristics, can address these challenges by enabling businesses to establish and maintain relationships with customers, expand their operational reach, and build a competitive advantage (De Vries et al., 2012).

The objective of this article is to evaluate marketing communication activities conducted by selected enterprises on social media. The analysis encompasses three companies representing different economic sectors: a food company (Company A), a cosmetics company (Company B), and a technology company (Company C). The study focuses on assessing key performance indicators (KPIs), such as the reach of published content and user engagement. Based on the collected data, a comparative analysis of effectiveness across selected social media

platforms - Facebook, Instagram, LinkedIn, YouTube, and TikTok - is conducted. The article seeks to answer four main questions:

The study seeks to determine which social media platforms are employed by the analyzed enterprises and the strategic motivations underlying their selection, to identify which publicly accessible indicators provide the most accurate assessment of communication effectiveness, to explore how sector-specific characteristics shape the efficiency of digital communication, and to establish what types of content prevail in the strategies implemented by the examined companies

2. Literature Review

To obtain the latest research findings on the use of social media by manufacturing enterprises - ensuring they are both valuable and of high quality - a desk research study was conducted, including a systematic literature review. Two databases were selected for this purpose: Web of Science and EBSCO. On January 7, 2025, searches were performed in both databases using the following phrases: “Social Media” AND “Manufacturing Companies,” “Social Media” AND “Manufacturing Companies” AND “Evaluation”, “Social Media” AND “Industrial Enterprises”, “Social Media” AND “Poland”, “Social Media” AND “Poland” AND “Case Study”, and “Social Media” AND “Łódź”.

The searches were restricted using the following criteria:

- Type: Peer-reviewed academic journals.
- Language: English and Polish.
- Publication date: January 5, 2015 - January 5, 2025.

Subsequently, a quality-based selection of the materials was performed. The author analyzed the relevance of the identified studies to the subject of the article by reviewing abstracts and eliminating duplicates. During the research process, numerous articles were found to be inaccurately indexed due to their keywords. Specifically, some articles included the term “Social” but did not address social media as online platforms; rather, they focused on employee behavior-mainly in the context of COVID-19. These articles were excluded. Additionally, studies whose findings were unrelated to the present article-such as those focused on customer relationship management (CRM) rather than social media platforms-were also omitted. Other excluded studies concentrated exclusively on production-related aspects, Industry 4.0, industrial innovations, and technological issues without any reference to the topic of this article.

After analyzing the search results, the literature was supplemented with additional sources that were not retrieved in the database searches-either due to the absence of relevant keywords or the publication date - the "snowballing” method. The final results of the desk research are summarized in Table 1.

Table 1.
Desk Research Results for the Article

	EBSCO	Web of Sience	Snowballing
Total Results	316	769	447
First Selection	85	45	67
Duplicate Removal	62		67
Final Results	129		

Source: Own elaboration.

2.1. The Role of Social Media in Marketing and Management

Social media have become an integral component of corporate communication strategies, encompassing both the B2C (Business to Client) and B2B (Business to Business) sectors (Hassani, Mosconi, 2022; Veldeman et al., 2017). Their primary advantage lies in the combination of global reach and personalized messaging, making them one of the most significant marketing tools for contemporary enterprises. Their role extends beyond brand image creation to include customer relationship management, marketing optimization, and audience engagement. In the context of manufacturing enterprises, social media facilitate effective outreach to customers, contractors, and business partners (Dao et al., 2024).

The literature highlights that one of the main challenges for this sector is the lack of adequately skilled personnel capable of effective communication and the limited involvement of managers in developing social media marketing strategies (Birkel, Müller, 2024; Conti et al., 2023; Milanzi, 2012). The technical complexity of products necessitates the adaptation of content to the specificities of the industry, posing a significant challenge in creating engaging and valuable digital content. These challenges are also observed in small and medium-sized enterprises, not only in the manufacturing sector but across various industries. Numerous studies have demonstrated that the ability to effectively manage social media directly influences business performance by increasing brand visibility, customer engagement, and market reach. Conversely, a lack of social media competencies significantly limits marketing potential, reducing competitive advantage and hindering adaptation to evolving consumer behaviors in the digital landscape (Kaczmarczyk, 2018; Müller et al., 2018).

A fundamental challenge for some enterprises is the very understanding of the concept of social media, as insufficient time has been dedicated to education in this domain. Kaplan and Haenlein (Kaplan, Haenlein, 2010) define social media as platforms enabling the creation, sharing, and interaction with user-generated content. Their primary advantage is the ability to merge global reach with message personalization, making them a crucial marketing tool for modern businesses. In the manufacturing sector, social media not only facilitate customer communication but also support B2B relationship building, enhance brand visibility, and enable more effective management of relationships with contractors.

One of the key aspects of effective social media utilization is user engagement, which constitutes a fundamental element of digital interactions. A systematic literature review reveals a rich body of research dedicated to this subject (Stepaniuk, 2024; Stopczyński, 2015; Tarapata,

2024; Zachurzok-Srebrny, 2024). Social media interactions influence brand perception, which translates into consumer loyalty and long-term engagement. Activities aimed at fostering engagement include content personalization, real-time interaction, and the use of analytical tools to optimize marketing campaigns.

Beyond user engagement, customer satisfaction remains a critical factor, serving as a metric for the effectiveness of digital interactions. Karpińska-Krakowiak (2016) (Karpińska-Krakowiak, 2016), Le Viet-Błaszczyk (Le Viet-Błaszczyk, Lerman, 2020), and (2020), as well as Samadi et al. (2016) (Samadi et al., 2016), indicate that customer satisfaction directly impacts brand loyalty, repeat purchases, and long-term engagement in the digital ecosystem. From the perspective of manufacturing enterprises, it is crucial to tailor content to industry-specific characteristics, considering the technical aspects of products and the needs of business customers.

Managing marketing activities on social media constitutes another significant research area. Effective social media marketing management is essential for brand positioning, audience engagement, and increasing the efficiency of promotional efforts (Bala et al., 2016; Caya, Mosconi, 2023). In the context of manufacturing enterprises, it is necessary to consider sector-specific characteristics, including the need to educate audiences about complex technological processes and the unique features of offered products. One of the latest trends in social media management by manufacturing firms is their use in educational initiatives, corporate social responsibility (CSR), and environmental sustainability. The literature highlights the social and ecological dimensions of social media utilization (Druffel, 2017; Imran et al., 2020). Furthermore, social media are analyzed in the context of health and psychological issues (Balcerowska, Brailovskaia, 2024) as well as digital education and communication (Al Saifi et al., 2016; Hahn et al., 2024; Malec et al., 2024). These studies suggest that social media can have a positive societal impact by raising ecological awareness, supporting educational initiatives, and increasing engagement in key social issues. Thus, the utilization of social media by manufacturing enterprises extends beyond traditional marketing functions to include relationship management, organizational policy shaping, and the implementation of pro-social and environmental initiatives. Modern firms that effectively integrate social media into their strategies not only enhance their market competitiveness but also contribute to broader goals in innovation, social responsibility, and education.

There are numerous social media platforms worldwide. Some emerged long ago and have since faded into obscurity, while others have sustained their relevance for over two decades. For the purposes of this study, five key social media platforms have been selected, on which manufacturing enterprises most frequently establish their presence.

Facebook, one of the oldest and most popular social media platforms, plays a significant role in companies' marketing activities (Forouzandeh et al., 2014). In Poland, the platform has 17.1 million users, making it one of the main communication tools for businesses (Kemp, 2024). Facebook offers various functionalities, including live streaming, posting texts, graphics,

and videos, as well as organizing events and advertising campaigns. Instagram, part of Meta's ecosystem (the owner of Facebook), is particularly attractive for visual industries such as fashion, cosmetics, or gastronomy (Legzdina, Sperlina, n.d.). With around 11 million users in Poland, Instagram ranks third among the most popular social media platforms. It offers various content formats, including photos, videos, Stories, and Reels, allowing for creative product and service presentation (Olejniczak, 2022; Stepaniuk, 2024). LinkedIn, as a platform connecting professionals, focuses on building business networks and promoting educational and expert content. With 6.7 million users in Poland, it is a crucial tool for companies operating in B2B and HR sectors (Deszczynski, 2018). By creating company pages, publishing articles, and industry content, LinkedIn enables building an expert image and strengthening brand positioning (Tsironis et al., 2022). The platform also stands out for its ability to conduct precisely targeted advertising campaigns, allowing companies to reach decision-makers and professionals in specific industries. TikTok, known for its short, engaging video formats, is gaining popularity in Poland, where it has 11.52 million users. This platform allows creative presentation of products and services through entertaining and inspiring content (Berg et al., 2023). YouTube, with 27.9 million users in Poland, remains the most popular video platform in the country. Its extensive possibilities for creating and distributing content make it essential for companies aiming to produce long, detailed video materials, such as tutorials, product reviews, or event coverage (Smith et al., 2012).

The literature points to several major functions of social media that can be used by companies - including manufacturing. Understanding them and using them appropriately is key to achieving the intended results. These are:

- Building brand awareness: Social media enables companies to reach a wide audience, increasing brand recognition (Wrona, 2012). Regular content publication helps build brand identity and shape consumer perceptions (Kitano et al., 2021).
- Two-way communication: Social media offers real-time interactions, allowing companies to promptly respond to customer needs and build lasting relationships (Klein, 2022; Skrobich, 2016; Zhang, Peng, 2024).
- Analyzing customer preferences: Advanced analytics tools enable companies to collect user behavior data, facilitating better alignment of marketing strategies (Dao et al., 2024; Gregor, Kaczorowska-Spychalska, 2016; Karpińska-Krakowiak, 2016).
- Creating engagement: Interactive content, such as contests, polls, or live streams, increases audience engagement, fostering loyalty to the brand (Androniceanu et al., 2020; Chin et al., 2018; Karpińska-Krakowiak, Modliński, 2018; Tran, Rudolf, 2022).
- Targeting and personalization: Social media platform algorithms enable precise targeting of specific audience groups based on interests, age, location, and other demographic data (Jabłońska, 2017; Pereira et al., 2024).

Beyond merely understanding the potential applications of social media, it is crucial to identify the parameters that allow for an evaluation of their utilization. Evaluation of social media activities should be based on measurable indicators. The literature identifies several key indicators for comprehensive marketing analysis. Three subgroups of these indicators will be utilized in this research to answer the posed questions:

- Reach: Defined as the number of unique accounts exposed to specific content on a platform, it serves as a key indicator of communication effectiveness in social media. However, it is essential to note that reach does not equate to the number of individuals exposed, as a single person may own multiple accounts on the same platform (Tomasik, Marona, 2023). Consequently, reach reflects only the number of unique accounts rather than users in the strict sense. This indicator is fundamental for assessing the visibility of published materials and analyzing the potential impact of communication (Kietzmann et al., 2011).
- Impressions: Referring to the number of times specific content is shown to users, impressions can be defined differently depending on the platform's specifics. All definitions share a common reference to the exposure of the content, regardless of user interaction. Notably, the same content may be shown multiple times to the same account, introducing a distinction between reach and impressions. The relationship between these indicators is described through the concept of frequency, indicating the average number of times the content is shown to a single user. In the literature, frequency plays a significant role in analyzing campaign effectiveness, influencing both brand awareness and potential audience reactions (Gręboszet al., 2016).
- Engagement: Reflecting the level of user interaction with published content, engagement includes commonly analyzed forms such as reactions, comments (Baj-Rogowska, Sikorski, 2023), and shares, varying depending on the platform's specificity. High engagement levels indicate the effectiveness of published content in attracting user attention and activating them. As Kotler (Kotler, Keller, 2015) emphasizes, engagement plays a crucial role in building relationships between the brand and its audience, serving not only as a content effectiveness indicator but also as a critical element of communication strategy. Analyzing engagement levels allows for better understanding of user preferences and behavior, enabling more effective content customization to meet audience needs.

Social media platform algorithms are among the most important factors determining marketing effectiveness. Each platform utilizes a unique set of rules influencing the content displayed to users. These mechanisms analyze hundreds of variables, such as user preferences, interaction frequency, content shared by friends, or paid advertising results (Brady et al., 2023). Facebook and Instagram (Meta): Algorithms prioritize content with high engagement levels, such as likes, comments, and shares. Video content and posts generating real-time interactions are favored (Kaplan, Haenlein, 2010). TikTok's For You Page (FYP) algorithm analyzes user

behavior, including time spent watching videos, number of repetitions, and reactions (e.g., likes and comments). TikTok promotes viral content, offering small businesses the opportunity to achieve significant reach without substantial financial investments (Gómez Sánchez et al., 2023). LinkedIn supports content optimized for professional and expert publications. Longer articles, infographics, and posts adding value in B2B segments are preferred (Davis et al., 2020). For YouTube, maximizing user time on the platform and ensuring displayed content aligns with user interests are crucial (Yesilada, Lewandowsky, 2022). Key factors include total time spent watching a video (Khan, 2017), engagement, and the click-through rate (CTR) for thumbnails relative to impressions (Arthurs et al., 2018).

Understanding algorithms, even approximately, provides companies with guidelines for action, showcasing which types of content are most preferred by platforms. Nevertheless, content creation remains the responsibility of promoting companies (or entities hired for this purpose). Engaging content lies at the heart of effective social media strategies. Research indicates that content evoking emotions, provoking reactions, and encouraging interaction is significantly more effective than purely informational content without emotional impact (Ashley, Tuten, 2015). Three main groups of elements contribute to engaging publications:

- Storytelling: Building narratives appealing to audience emotions is a crucial aspect of engaging content. Companies presenting authentic stories, such as customer experiences or behind-the-scenes insights, build greater trust and loyalty (Júnior et al., 2023).
- Multimedia: Research shows that visual content, such as images, infographics, and videos, generates 150% more interactions than textual content (Tafesse, Wien, 2017). In particular, videos have viral potential, reaching a wide audience with minimal advertising budgets.
- Interactivity: Polls, contests, live broadcasts, and other interactive forms capture attention and encourage active user participation (Nie et al., 2023).

Engaging content directly impacts performance indicators, such as reach, impressions, time spent on the platform, or customer loyalty. Companies employing storytelling and interactive content achieve higher sales results and greater brand recognition (Ashley, Tuten, 2015).

2.2. Effectiveness, Efficiency, and Performance: Foundations for Evaluation

Managing communication, particularly in the area of social media marketing activities, requires a clear definition of effectiveness, efficiency, and performance, which enable the evaluation of key actions. Effectiveness refers to achieving intended goals regardless of the resources and means used, which, according to Kotarbiński (Kotarbiński, 1955), constitutes the fundamental determinant of success. Griffin (Griffin, 2017) associates effectiveness with "making the right decisions and effectively implementing them." Piłejko (Piłejko, 1976), on the other hand, emphasizes the purposefulness of actions, determining effectiveness as the alignment of results with intended objectives. Efficiency, as defined by Zieleniewski (Zieleniewski, 1976), involves optimizing the use of available resources, emphasizing

rationality and economy. Performance, integrating both elements, allows for assessing success in achieving goals with minimal expenditure (Holstein-Beck, 1987). It is essential to recognize that the success of marketing activities often depends on simultaneously achieving defined objectives, effectively allocating resources, and responding to dynamically changing user preferences (Pócs et al., 2021). Actions taken by enterprises on social media largely depend on platform algorithms, which determine content visibility (Brady et al., 2023). Therefore, a thorough analysis, considering operational and strategic efficiency, can be valuable in evaluating whether social media activities yield the desired results.

3. Methods

The primary objective of this research was to evaluate the effectiveness of communication activities conducted in social media by selected manufacturing companies from the Łódź Province in Poland. The analysis was based on the observation of the activity of three firms representing different sectors: food, cosmetics, and heavy industry. Company A is a manufacturing enterprise from the food sector, located in the Łódź Voivodeship, specializing in accessories and components for home food production. Its product portfolio focuses on solutions supporting, among others, bread baking, liqueur preparation, and food preservation, designed for practical application by individual consumers. Company B is a Polish cosmetics manufacturer and brand with over 25 years of experience. It specializes in facial and body care products, make-up, as well as hair coloring and hair care. The company operates internationally, reaching more than 60 markets worldwide. Its business model combines the sale of proprietary brands (B2C) with contract manufacturing services (B2B). Company C, representing the heavy and technology industry, employs a markedly different approach to social media than consumer-oriented enterprises. While B2C firms focus on generating broad reach and engaging audiences through visual and emotional content, Company C's primary objectives are to build credibility, secure institutional legitimacy, and showcase expert competences.

This allowed for the identification of diverse approaches to digital communication shaped by sectoral characteristics. The study focused on publicly available data published on the official company profiles in social media platforms (Facebook, Instagram, LinkedIn, TikTok and YouTube), including posting frequency, user interactions, engagement rate in relation to follower bases, and video viewership where such information was publicly accessible. The research also incorporated an analysis of the structure of published content, distinguishing between educational, image-building, and sales-oriented materials, as well as between various content formats such as graphics, videos, and text-based posts.

The study was designed to answer four key research questions:

1. which social media platforms are used by the analyzed enterprises and what are the reasons for their selection?
2. which publicly available indicators most accurately reflect the effectiveness of communication activities?
3. how industry characteristics influence communication efficiency?
4. what types of content dominate in the strategies of the examined companies?

In order to provide answers to these questions, the case study method was adopted, which enables an in-depth characterization of organizations and the identification of specific activity patterns. The choice of this method was motivated by the need to capture the complex context of digital communication, which would be difficult to reconstruct solely by means of quantitative techniques (Apanowicz, 2000, 2002; Czakon, 2015; Eisenhardt, Graebner, 2007; Strumińska-Kutra, Koładkiewicz, 2018). The research process consisted of several stages. In the first phase, semi-structured interviews were carried out with decision-makers responsible for social media activities in the analyzed companies. The aim was to gain an understanding of the organizational perspective and to uncover the vision and strategy guiding their social media presence. The use of interviews is consistent with the recommendations of qualitative marketing research, which stresses their ability to uncover motivations and attitudes shaping consumer-brand relations (Hall, 2019; Maison, 2018). In parallel, an inventory of the social media platforms employed by the companies was performed, and data were collected on the number of followers, the number of posts published during the analyzed period, and user interactions with content. Subsequently, a qualitative content analysis was conducted, classifying posts according to their communicative functions and formats, in line with established methodological frameworks (Krippendorff, 2019; Kaczmarczyk, 2011). The quantitative data were standardized using relative indicators such as the average number of interactions per post and the engagement rate calculated as the ratio of reactions, comments, and shares to the total number of followers. This standardization made it possible to perform comparative analyses both across companies and across platforms. It highlighted sectoral differences and similarities in applied strategies.

The analysis was descriptive and comparative in nature and was performed using data triangulation, which combined direct observation of company profiles and verification of activity via publicly available advertising libraries. This triangulated approach strengthened the validity of the findings and reduced the risk of bias arising from a unilateral treatment of empirical material (Dwivedi et al., 2021; Li et al., 2023; Lipowski et al., 2018). The selection of companies was purposeful, motivated by both sectoral diversity and accessibility considerations, since the participating enterprises granted full consent for the study. Such purposive sampling is consistent with methodological standards in marketing and management research (Apanowicz, 2002; Kaczmarczyk, 2014). It is important to note that the study is subject to certain limitations, primarily related to the lack of access to complete internal

datasets such as results of paid advertising campaigns or financial indicators like ROI or ROAS. For this reason, the assessment of effectiveness was restricted to the dimension visible in the public domain, namely user interactions and content characteristics. The literature emphasizes that the mere volume of likes, comments, or shares does not allow for an objective evaluation of communication effectiveness, as these values are strongly dependent on the size of the community surrounding a given profile. For this reason, empirical research widely applies the Engagement Rate (ER), which normalizes the number of interactions in relation to the follower base (Trunfio, Rossi, 2021). This method enables comparisons of effectiveness both across different platforms and between enterprises with varying scales of digital presence. In its simplest form, the indicator is defined as follows (1):

$$ER = \frac{Total\ Interactions\ (Reactions + Comments + Shares)}{Number\ of\ Followers} * 100\% \quad (1)$$

Such a defined indicator reflects the proportion of the community that actively responds to published content and is widely applied in comparative analyses of social media communication effectiveness in both B2C and B2B contexts. The analysis did not capture long-term outcomes, since the study adopted a cross-sectional approach limited to a twelve-month period (January - December 2023). Despite these limitations, the chosen methodology enabled a reliable reconstruction of the communication strategies of the enterprises and the identification of the key factors determining the effectiveness of their social media presence.

4. Research results

In order to ensure a transparent and systematic presentation of the empirical material, all collected data have been compiled in the tables below. These datasets summarize the social media activities of the analyzed enterprises across various platforms, including Facebook (Table 2), Instagram (Table 3), TikTok (Table 4), and YouTube (Table 5). The tables include key indicators such as the number of posts, user reactions, comments, shares, and views, as well as calculated engagement rates. Such a standardized presentation facilitates comparative analysis across companies and platforms, and provides a clear empirical basis for further interpretation. Table 1 provides an overview of the monthly communication patterns of the analyzed companies on Facebook. It highlights the intensity of posting activity and the scale of user engagement, offering a basis for comparing sector-specific approaches to the same platform.

Table 2.
Facebook Activity of Companies A, B, and C (Posts, Reactions, Comments, Shares)

	Company A				Company B				Company C			
Month	**Number of Posts**	**Total Reactions**	**Total Comments**	**Total Shares**	**Number of Posts**	**Total Reactions**	**Total Comments**	**Total Shares**	**Number of Posts**	**Total Reactions**	**Total Comments**	**Total Shares**
January	12	253	6	24	16	675	71	44	2	35	1	1
February	9	116	0	6	19	764	23	34	7	93	0	0
March	9	122	20	5	20	1187	124	108	14	188	0	0
April	10	115	8	3	23	1433	170	107	12	107	0	5
May	9	82	12	8	29	1911	340	129	8	91	1	2
June	8	16 153	249	994	24	1768	266	105	5	71	0	2
July	10	273	6	17	27	1944	142	149	8	145	2	10
August	9	173	21	6	23	2167	303	58	14	131	3	5
September	3	46	1	9	25	2344	230	114	17	170	1	3
October	10	132	18	22	29	2995	651	105	9	64	0	0
November	16	296	3	36	30	1865	202	36	6	61	1	1
December	17	308	12	18	35	3099	282	122	9	103	2	2
Total	**122**	**18 069**	**356**	**1148**	**300**	**22152**	**2804**	**1111**	**111**	**1259**	**11**	**31**

Source: Own elaboration based on data from Facebook.

The results indicate that engagement outcomes are shaped more by the logic of content strategy than by posting frequency. Facebook activity illustrates that the ability to stimulate user interaction depends on the alignment of content with audience expectations rather than on the volume of publications. Table 2 summarizes the use of Instagram by Companies A and B, capturing their monthly posting activity and audience responses. The dataset illustrates how a visually oriented platform supports branding strategies in different industries.

Table 3.
Instagram Activity of Companies A and B (Posts, Reactions, Comments)

	Company A			Company B		
Month	**Number of Posts**	**Total Reactions**	**Total Comments**	**Number of Posts**	**Total Reactions**	**Total Comments**
January	10	345	2	11	2575	130
February	7	309	2	11	2034	114
March	13	5404	12	10	1870	114
April	5	19825	122	14	4167	160
May	11	4618	16	16	4576	180
June	4	572	11	12	3378	109
July	6	3305	30	13	4389	204
August	4	1123	9	10	2798	84
September	0	0	0	12	3323	86
October	11	267	3	12	2840	112
November	12	411	7	13	3192	164
December	20	444	14	17	3370	142
Total	**103**	**36623**	**228**	**151**	**38512**	**1599**

Source: Author's elaboration based on data from Instagram.

The findings suggest that Instagram functions mainly as a tool for visual identity building. Engagement is characterized by seasonal peaks and campaign-driven effects, showing that content timing and aesthetics play a greater role than numerical activity alone. Table 3 presents the presence of Companies A and B on TikTok, focusing on publishing frequency, audience reach, and forms of interaction. This perspective allows for an assessment of how short video formats influence communication outcomes.

Table 4.
TikTok Activity of Companies A and B (Views, Reactions, Comments, Saves)

	Company A					Company B				
Month	**Number of Posts**	**Total Views**	**Total Reactions**	**Total Comments**	**Total Saves**	**Number of Posts**	**Total Views**	**Total Reactions**	**Total Comments**	**Total Saves**
January	4	301 065	9 301	124	3 233	9	24 686	404	25	110
February	5	426 337	10 706	204	2 798	10	11 632	344	22	52
March	11	419 583	7 271	229	2 121	11	31 575	4328	112	63
April	5	4 149 500	204 433	1 773	42 308	9	16 473	352	24	42
May	5	2 864 200	121 713	785	17 709	9	12 345	321	21	38
June	3	1 259 600	50 929	417	10 969	15	96 317	865	34	64
July	6	965 489	29 509	301	7 149	10	225 957	1401	32	44
August	2	278 100	6 081	216	2 302	12	345 921	1300	29	86
September	1	15 700	614	8	111	12	293 265	2201	51	42
October	1	1 725	15	0	2	15	636 027	2999	156	94
November	1	1 744	9	0	0	10	58 804	390	23	37
December	3	146 461	1 287	79	513	10	163 142	1750	52	28
Total	**47**	**10 829 504**	**441868**	**4136**	**89215**	**132**	**1 916 144**	**16655**	**581**	**700**

Source: Own elaboration based on data from TikTok.

The results highlight the volatility of TikTok performance. Engagement is strongly dependent on a limited number of highly effective materials, while most content attracts moderate attention. The platform demonstrates the importance of trend adaptation and creativity in driving user activity. Table 4 compiles the activity of all three companies on YouTube, including posting patterns and levels of user interaction. It provides a basis for evaluating YouTube's function in long-form and educational communication.

Table 5.
YouTube Activity of Companies A, B, and C (Views, Reactions, Comments)

	Company A				Company B				Company C			
Month	**Number of Posts**	**Total Views**	**Total Reactions**	**Total Comments**	**Number of Posts**	**Total Views**	**Total Reactions**	**Total Comments**	**Number of Posts**	**Total Views**	**Total Reactions**	**Total Comments**
January	3	9 227	398	53	5	2462	14	1	1	35163	11	0
February	2	468 000	6 000	122	0	0	0	0	1	26627	6	0
March	6	96 700	1 657	30	0	0	0	0	0	0	0	0
April	3	265 300	5 779	107	11	2326	8	1	1	1068	10	0
May	1	389 000	12 000	93	4	42 830	3	1	0	0	0	0
June	2	32 850	1 130	21	0	0	0	0	3	12241	12	0
July	4	1 392 148	30 831	638	5	834	5	0	2	756	10	0
August	3	70 623	2 257	61	0	0	0	0	6	263	2	0
September	0	0	0	0	3	336	1	0	0	0	0	0
October	1	2 200	69	2	1	285	1	0	0	0	0	0
November	2	4 500	77	4	3	285	4	1	0	0	0	0
December	3	6 465	146	4	1	118	0	0	0	0	0	0
Total	**30**	**2 737 013**	**60 344**	**1135**	**33**	**49476**	**36**	**4**	**14**	**76 118**	**51**	**0**

Source: Own elaboration based on data from YouTube.

The outcomes confirm that YouTube acts mainly as a supporting channel. While individual materials can generate visibility, long-term engagement requires strategic commitment and consistent positioning. Without such effort, the platform tends to serve as a passive content repository.

The three analyzed enterprises pursued markedly different strategies of social media communication, which directly stemmed from the characteristics of their respective industries. Company A**,** operating in the food sector, concentrated its presence primarily on Facebook, where it gathered 23,282 followers and published 122 posts. The content was predominantly educational and utilitarian in nature, including tutorials and video materials demonstrating practical applications of products (bread baking, liqueur preparation, homemade preserves). Strictly sales-oriented and image-building content appeared only sporadically. A single viral video published in July generated 2.38 million views, representing 82% of the total annual reach (2.9 million). This exceptional result overshadowed the performance of other posts. This mechanism also translated into the dynamics of follower growth. In the same month the profile expanded by 8600 new followers, representing 83% of the annual increase. In the remaining months, growth amounted only to several dozen individuals, while average user activity remained low: the median was 13 reactions, 0 comments, and 1 share per post. The only exception was June, when the viral video generated more than 2000 reactions to a single post. A similar lack of systematicity characterized Instagram, where the company gathered 10,900 followers and published 103 posts, generating a total of 36,979 interactions (an average of 358 per post). Annual reach amounted to 810,900, with as much as 68% concentrated in May (552,700), whereas in the weakest months values fell to the level of 7900. User activity was almost exclusively limited to reactions (≈99%), while comments accounted for barely 1% of all interactions. The most important platform for this company, however, was TikTok, where 47 published videos obtained 10.83 million views and 535,200 interactions, averaging 11,400 interactions per video. The profile had 67,500 followers and 443,700 likes. April and May alone generated around 65% of annual views. Including June and July, the four months together accounted for more than 85% of the total. Engagement was dominated by reactions (82.6%), followed by saves (16.7%), while comments played only a negligible role (0.8%). YouTube functioned as an educational and instructional channel - 30 videos generated 2.74 million views and 61,500 interactions, averaging 91,000 views and 2000 interactions per video. The best results were achieved in July (1.39 million views, ≈51% of the annual outcome), confirming the concentration of effects in single pieces of content. In contrast, presence on LinkedIn was marginal - the profile had 1041 followers and 181 declared employees, while the content had an expert and employer branding character, without the support of paid campaigns**.** Company B**,** representing the cosmetics sector, conducted a more systematic and diversified communication. On Facebook (81,100 fans), 300 posts were published, corresponding to an average of 25 entries per month. These posts generated 22,152 reactions, 2804 comments, and 1111 shares, yielding 26,067 interactions in total (87 per post on average). The highest engagement was recorded in October (129 per post), the lowest in February (43 per post), while the median indicated that a typical post generated 69 reactions, 5 comments, and 2 shares. The interaction structure confirmed the dominance of reactions (85%). These activities were strongly supported by 261 paid campaigns in the Meta ecosystem - 210 on Facebook,

150 on Instagram, as well as additionally in Messenger (83) and Audience Network (93). On Instagram (38,300 followers), the company published 151 posts, which generated 38,512 reactions and 1599 comments (40,111 interactions in total, 266 per post on average). The best results were achieved in July (353 per post) and the weakest in February (195 per post), with the highest engagement occurring during product launch periods (April-May). Reactions constituted 96% of all interactions, whereas comments played only a marginal role. On LinkedIn, the profile gathered 4,937 followers and 148 employees. Corporate, HR, and employer branding content was published, while paid campaigns appeared only three times. TikTok constituted an important element of the strategy - the profile had 67,500 followers and 443,700 likes, while 132 published videos generated 1.92 million views and 17,900 interactions (136 per post on average). The median results were low (943 views and 126 likes per post), proving that most content achieved moderate reach, with annual results boosted by a few standout materials. A significant role was played by 56 advertising campaigns on TikTok, which reached 6.28 million unique users and accounted for ≈38% of all views. YouTube was the least effective channel. The profile has existed since 2014 (487 videos, 9.07 million total views), in the period under review only 33 videos were published, generating 49,500 views (1500 per video on average). Results were concentrated in May (42,800 views, ≈87% of the yearly total), but user activity was minimal - 36 reactions and 4 comments. Company C, from the heavy industry and technology sector, conducted communication typical of B2B, focusing on professional image-building and credibility. On Facebook (80,000 global followers, 111 posts on the Polish channel), the company recorded 1,259 reactions, 11 comments, and 31 shares (1301 interactions in total, 11.7 per post on average) - in Polish profile context. The highest results were achieved in July (19.6 per post) and the lowest in October (7.1 per post). Annual reach amounted to 245,600, with July and August accounting for 59% of the total. Annual follower growth was minimal - only 137 individuals (0.17% of the base). The company did not maintain accounts on Instagram or TikTok. The main communication channel was LinkedIn, where the global profile gathered 303,102 followers and 11,692 employees linked to the account, including 235 from Poland (39 in managerial and directorial positions). The strategy encompassed corporate content (projects, certifications), recruitment, and expert-product materials, with multilingual communication (English and occasionally Polish) as a distinctive feature. YouTube played a marginal role - 14 videos were published, generating 76,100 views and only 51 reactions without comments. Performance was uneven: over 80% of annual views came from January and February. By contrast, in August six published videos attracted only 263 views in total (≈44 per video). The average interaction rate amounted to merely 3.6 per post, confirming that the channel served solely an informational and archival function.

The analyses and interviews conducted allowed for the identification of characteristic patterns of social media communication in the studied enterprises. On this basis, it became possible to provide answers to the research questions that constituted the starting point of this

study. The conclusions are presented below in accordance with the adopted structure of the research problems. The core of Company A's ecosystem includes Facebook, Instagram, TikTok, and YouTube, with functions distributed across channels. Facebook served as the primary medium for practical and instructional content (122 posts; 23,282 followers; annual reach ≈2.89 million, with a strong peak in July confirming the incidental nature of a viral effect). Instagram functioned as a supplementary platform (10,900 followers; 103 posts; total reach ≈811,000), TikTok was used for short DIY formats (47 videos; 10.83 million views, with a significant surge between April and May, again confirming the incidental nature of viral exposure), while YouTube focused on educational and instructional materials (30 videos; 2.74 million views; entirely organic activity). The main motivation for this choice was the educational function. As the marketing manager stated: *This is not advertising, but real assistance*. All activities aimed to build consumer trust and loyalty toward utilitarian products. Platforms were selected according to their format (short videos vs. longer tutorials) and the expected behaviors of their audiences.

Company B (cosmetics) also developed a multi-channel ecosystem with a strong presence on Facebook (300 posts; 26,067 total interactions), Instagram (38,300 followers; 151 posts; 40,111 interactions), TikTok (132 videos; 1.92 million views; 17,936 interactions), and YouTube (33 videos; 49,476 views). Additionally, broad paid support was implemented across Meta platforms (261 campaigns). The rationale for prioritizing Instagram and TikTok lies in the visual and emotional nature of communication and the use of influencers. As the marketing director emphasized: *This is where our customers live - they seek inspiration and storytelling*. LinkedIn played a complementary role, focused on corporate and HR communication. Company C (heavy industry) maintained a narrow platform profile, aligned with B2B objectives. Key channels were LinkedIn (global profile with 303,102 followers, 11,692 linked employees; 235 from Poland) and Facebook (111 posts on the Poland-dedicated channel; 1,301 interactions; annual reach of 245,600). The company deliberately avoided Instagram and TikTok. YouTube played only a marginal role (14 videos, 76,118 views, ≈81% of annual traffic concentrated in January - February), functioning mainly as a content archive. As the marketing manager summarized, the company's actions were guided by a precise goal: *What matters is reaching decision-makers and building expert legitimacy, not mass reach*. Across all three enterprises, the necessity of social media presence was strongly emphasized, perceived as a prerequisite of credibility and market visibility: *It is not about whether it is profitable - it is a necessity*. Platform choices were thus subordinated to function, target group, and the specific affordances of individual media.

The assessment of social media effectiveness was based on a triangulated approach that combined qualitative content analysis with the verification of quantitative indicators such as engagement rate, average number of interactions per post, reach, follower growth, and the share of comments and shares in total interactions. The selection of these indicators was dictated by the limitations of the study. Only publicly available data and partial insights from analytics

panels were accessible, without full results of paid campaigns (ROI, ROAS) or financial outcomes.

As shown in Table 6. Company A reports the highest Engagement Rate values (793% on TikTok, 339% on Instagram, 322% on YouTube). These outcomes are largely the result of isolated viral content. The median interaction level on Facebook (13 reactions, 0 comments, 1 share) demonstrates that average user activity was negligible. This implies that spectacular results were incidental and do not confirm a sustained ability to engage the community. Critically, it should be noted that this strategy relies more on chance than on a consistent content management model. Company B is characterized by greater stability (105% on Instagram, 446% on TikTok), supported by regular posting and paid campaigns. Nonetheless, the low level of interaction on YouTube (ER ≈1%) and the moderate performance on Facebook (32%) indicate a lack of cross-platform consistency and the inability to fully exploit the potential of multi-channel communication. A further critical observation is the dominance of simple reactions over comments, which reduces communication to passive content consumption. Company C performs the weakest in quantitative terms (Facebook ER 1.6%; YouTube 35.7% based on a subscriber base of only 143). The relatively high percentages are solely an artefact of the small sample size, rendering them unreliable. The absence from Instagram and TikTok, along with marginal YouTube activity, significantly limits brand visibility, and reliance on the qualitative value of a few individual comments cannot substitute for systematic and scalable communication.

Table 6.
Engagement Rate by Platform (Facebook, Instagram, TikTok, YouTube)

Platform	Company A	Company B	Company C
Facebook	189 %	32 %	1,60 %
Instagram	339 %	105 %	-
TikTok	793 %	446 %	-
YouTube	322 %	1 %	35,7 %

Source: Own elaboration.

In summary, all three strategies reveal significant shortcomings: Company A is dependent on viral content, Company B relies excessively on paid promotion and generates predominantly passive engagement, while Company C limits its activities to reputational efforts without achieving real visibility. As a result, none of the analyzed organizations presents a communication model that could be regarded as sustainable, coherent, and strategically comprehensive. It should also be emphasized that the Engagement Rate represents only one indicator of effectiveness, and a complete assessment can be achieved only when financial outcomes are considered. The present results are based solely on visible metrics, without examining their translation into sales, new customer acquisition, or business inquiries.

Industry characteristics fundamentally shape both the logic of social media presence and the actual effectiveness of communication activities. In consumer-oriented sectors (B2C), effectiveness is determined by the ability to generate reach and emotionally engage audiences.

In industrial sectors (B2B) it depends on building reputation and fostering qualitative relationships with narrow groups of stakeholders. In the food industry (Company A), the core characteristic lies in the functional nature of products, which translates into the dominance of educational and instructional content. Communication effectiveness here results from the practical utility of published materials-audiences engage when they perceive real value (e.g., recipes, guides, tutorials). In the cosmetics industry (Company B), aesthetics and lifestyle serve as integral elements of the offering. Communication becomes a vehicle for visual narratives, in which products are presented in an aspirational context. However, a defining feature of this sector is the predominance of simple reactions (likes), while comments and discursive content remain limited. Thus, communication generates engagement, but in a predominantly superficial form. In the heavy industry (Company C), sectoral characteristics define an entirely different logic. Products are highly specialized, and audiences are narrow and decision-making oriented. Communication effectiveness is not measured by the number of reactions but by reaching the right individuals and building institutional credibility. Consequently, expert and corporate content dominates. In this case, algorithms or seasonality are of minor relevance-effectiveness is defined by the quality of interactions and the reputational nature of messaging. In summary, industry characteristics directly determine communication effectiveness. In B2C sectors, the usefulness and attractiveness of content drive engagement scale. In B2B, the specialized character of products and processes means that effectiveness depends on qualitative access to decision-makers and the reinforcement of expert reputation.

In the case of Company A, the dominant role is played by practical content. These include primarily instructional recordings, recipes, and visual demonstrations of how products can be used in everyday household activities. Such an approach not only strengthens the brand's credibility but also facilitates the creation of a community of users centered around a specific lifestyle. Company B builds its communication on emotion- and aesthetics-driven messages. The most frequent materials are visual content related to skincare, fashion, and styling, complemented by narratives that construct an aspirational image of the brand. A significant role is played by collaborations with public figures and influencers, who present products in natural contexts, highlighting their attractiveness and distinctive character. By contrast, Company C emphasizes specialized and image-oriented materials. Publications focus primarily on technological innovations, sustainability projects, and corporate reports. Such content is not designed to engage a broad audience but rather to reinforce the company's position as a credible business partner and an organization with an established reputation.

5. Discussion

Research conducted among selected manufacturing companies from the Łódź Voivodeship demonstrated that the effectiveness of social media communication is determined by sectoral conditions, organizational resources, and the manner of content creation. These findings partly confirm the literature but also problematize and challenge it in several respects. Dwivedi et al. (Dwivedi et al., 2021) indicate that in B2B contexts, social media presence is primarily institutional. The results corroborate this view: managers consistently emphasized that absence from social platforms equates to a loss of visibility and credibility. However, the experience of Company C illustrates that institutionalization alone does not translate into effectiveness - the company's Facebook and YouTube profiles recorded minimal interaction. This shows that the obligation of digital presence described by Kaplan and Haenlein (Kaplan, Haenlein, 2020) is not synonymous with communicative success. In the case of Company A, whose activities were based on educational content, the findings did not unequivocally confirm Hollebeek and Macky's (Hollebeek, Macky, 2019) thesis that content marketing gradually builds trust. Annual outcomes were determined by a single viral piece of content, proving that algorithms and incidental spikes are as influential as long-term strategies. This partially corresponds with the observations of de Vries, Gensler and Leeflang (de Vries et al., 2017), yet simultaneously undermines Kowalska's (Kowalska, 2023) vision of linear community-building through education. Company B, representing the cosmetics industry, confirmed the importance of visual narratives and influencers highlighted by Casaló, Flavián and Ibáñez-Sánchez (Casaló et al., 2020) and Djafarova and Trofimenko (Djafarova, Trofimenko, 2019). The dominance of simple reactions indicates that storytelling (Stopczyńska, 2016) and authenticity do not always result in deep interaction. In practice, communication was superficial, contradicting literature that assumes such content generates lasting ties. In the industrial sector (Company C), theory also found only partial confirmation. Iankova et al. (Iankova et al., 2019) and Lashgari et al. (Lashgari et al., 2018) stress that in B2B contexts, the quality of interactions is decisive. Yet our data reveal that even with an expert tone and professional image, communication remained marginal and interactions were almost absent. This suggests that the reputational role of social media, discussed by Mazurek-Łopacińska and Sobocińska (Mazurek-Łopacińska, Sobocińska, 2022), is not always borne out in practice - especially in firms with limited marketing resources operating in local markets. The issue of regularity likewise requires clarification. Laradi et al. (Laradi et al., 2023) and Lamberton & Stephen (Lamberton, Stephen, 2016) argue that systematic activity strengthens brand equity and trust. However, in Company B, despite high posting regularity, interactions were predominantly superficial. This suggests that regularity is a necessary but insufficient condition. The lack of resources, highlighted by managers from Companies A and C, supports the observations of Rydzewska and Szwajca (Rydzewska, Szwajca, 2024) regarding personnel and technological barriers in

SMEs. At this point, it becomes evident that the effectiveness of social media communication in manufacturing enterprises cannot be fully explained by frequency or visibility indicators alone but must be understood through the prism of relationship marketing and value communication theories. The analyzed companies demonstrated that what truly drives engagement is not the volume of messages but the ability to deliver perceived value - functional, emotional, or epistemic - corresponding to the audience's expectations. In this respect, Company A exemplified functional value communication (utility and education), Company B emotional and symbolic value (aesthetic and aspirational storytelling), and Company C epistemic value (expert knowledge and professionalism). These patterns confirm that value transmission, rather than direct relationship-building, dominates the communication logic of industrial actors, extending the classical understanding of relational marketing beyond emotional attachment toward knowledge-based and credibility-driven exchanges. The findings align with Appel et al.'s (Appel et al., 2020) perspective that social media constitute the foundation of modern marketing, but (in this particular context) they serve more a communicative than a relational role. In the Polish context, Kaczorowska-Spychalska (Kaczorowska-Spychalska, 2018) rightly notes that digital presence has become standard, though not synonymous with effectiveness. Industry reports such as Gemius/PBI (Gemius/PBI, 2025) also confirm that over 85% of Polish industrial firms are on social media, and 90% of internet users engage with these platforms. Yet our research shows that ubiquity does not guarantee effectiveness - results are extremely uneven and often dependent on viral phenomena. On the other hand, the findings partially confirm the conclusions of Grębosz, Siuda and Szymański (Grębosz et al., 2016), who note that practical and educational content fosters community-building around products. For Company A, this was visible in user comments, where customers reported undertaking actions inspired by video tutorials, though the effect proved short-lived and irregular. It is also worth referring to earlier sources. Howaniec (Howaniec, 2023) emphasized the role of social media in value-based marketing, while our findings show that educational value exerted stronger impact than brand presence alone. Buchnowska (Buchnowska, 2013) pointed to the low level of social media adoption among Polish firms, a claim no longer valid - today social media are ubiquitous, shifting the key question from "whether to be present" to "how to be effective." The conclusions of our study are also polemical in relation to foreign theses. Kapoor et al. (Kapoor et al., 2018) stressed the rapid development of social media research, while Arora et al. (Arora et al., 2019) measured influencer impact across platforms. Company B's results, however, show that influencer impact does not always foster dialogicality. Biedenbach, Hultén & Tarnovskaya (Biedenbach et al., 2019) analyzed brand equity management in B2B, yet Company C failed to translate such strategies into tangible results. Similarly, Salo (Salo, 2017) called for further research into social media in industrial marketing - our results validate this postulate, as traditional reach metrics fail to capture real effectiveness. Felix et al. (Felix et al., 2017), by contrast, proposed holistic frameworks of social media marketing balancing sales, reputational, and engagement content.

The analyzed firms' results show such balance was lacking. The broader historical context must also be considered. Koponen and Julkunen (Koponen, Julkunen, 2022) analyzed traditional industrial communication strategies based on long-term relations and personal contacts. Compared with these, contemporary digital strategies appear fragmented and more dependent on accidental viral effects than on consistent relationship-building. In conclusion, the findings indicate that although social media are ubiquitous and indispensable, their actual effectiveness in the manufacturing sector remains limited. Contrary to much of the literature, which emphasizes gradual relationship-building (Hollebeek, Macky, 2019; Howaniec, 2023), narrative strategies (Casaló et al., 2020; Stopczyńska, 2016), or qualitative B2B interactions (Iankova et al., 2019), our research demonstrates that outcomes depend more on algorithms, paid promotion, organizational resources, and sectoral characteristics than on communication strategies alone. Moreover, the obtained results strengthen the theoretical linkage between relationship marketing and value communication by demonstrating that, in manufacturing contexts, social media primarily serve as tools of functional value transmission rather than deep relational engagement. They show that emotional bonds with customers - so central in consumer markets - are often replaced by credibility- and utility-based exchanges. Consequently, the findings extend the concept of relationship marketing by introducing the notion of "operational relationship maintenance", where the goal is not to create long-term emotional ties but to maintain continuous visibility and informational relevance. At the same time, they challenge the assumption that relational marketing naturally translates into measurable online engagement, suggesting the need for a revised model integrating technological, algorithmic, and sectoral determinants of digital communication effectiveness.

6. Conclusions

The conducted research confirmed that the effectiveness of social media communication in manufacturing enterprises is shaped by multiple factors, most notably industry-specific conditions, the type of content, and the coherence of the adopted strategy. The analysis revealed that in consumer-oriented sectors, effectiveness derives primarily from the ability to produce visual and practical content that addresses user needs and facilitates the creation of an emotional bond with the brand. At the same time, significant limitations were identified, including an excessive reliance on viral effects, which generate high performance indicators only temporarily, and the dominance of simple reactions over dialogic forms of interaction. In industrial sectors, effectiveness assumes a different form, where the crucial element is the strengthening of reputation and the establishment of expert credibility, even in the face of low quantitative indicators. A critical reflection on the study highlights several limitations that should be addressed in future research. First, the reliance on publicly available indicators

excluded the possibility of assessing financial efficiency, which makes it difficult to determine the actual business value of social media communication. Second, the cross-sectional design captured only short-term outcomes, leaving unanswered questions about the sustainability of strategies and their long-term impact on organizational growth. Third, the uneven distribution of engagement, often concentrated around single posts or campaigns, indicates that the results may be strongly affected by external factors such as algorithms or seasonal trends, limiting their generalizability. Based on the conducted research, interviews, and analytical work, several recommendations can be formulated. First, effective communication requires a balance between content designed for broad reach and content of a more in-depth nature, which fosters long-term engagement and customer loyalty. Excessive dependence on viral effects or simple reactions leads to short-term outcomes that do not translate into stable brand development. Second, while the development of multi-channel strategies is essential, it must be consistent and coherent. Neglecting certain platforms reduces the ability to exploit their potential, whereas fragmented activities without a unified narrative result in an inconsistent image. Third, the evaluation of effectiveness should rely on a comprehensive set of indicators. Absolute metrics, such as the number of likes or views, are insufficient. Relative measures such as engagement rate, median interactions, or concentration indexes should be applied. Fourth, it is recommended to integrate community activity indicators with business metrics, including lead generation, client acquisition, or sales growth, in order to capture the actual translation of digital communication into organizational objectives. Despite these weaknesses, the study contributes new knowledge by showing that social media effectiveness in manufacturing enterprises is not defined by the scale of activity but by its alignment with sectoral logic and strategic coherence. The findings emphasize that consumer-oriented firms benefit most from content that combines utility and emotional appeal, while industrial companies rely primarily on credibility and expertise. This distinction enriches the theoretical debate on relationship marketing by demonstrating that engagement metrics alone cannot serve as a universal benchmark across different business contexts. From a practical standpoint, the research indicates that companies should not only measure visible interactions but also link digital activities to concrete business outcomes, such as lead generation, client acquisition, or reputation building. Integrating quantitative metrics with qualitative evaluation enables organizations to identify communication patterns that contribute to sustainable competitive advantage. Furthermore, the results may serve as a reference point for SMEs, which often operate under resource constraints, helping them to prioritize investments in digital competences and long-term strategic planning. In conclusion, the empirical findings indicate that the effectiveness of social media communication in manufacturing enterprises does not stem from a single dominant factor but from a complementary approach that combines industry adaptation, conscious use of content formats, cross-channel consistency, and rigorous evaluation of results. Only such an integrated perspective allows social media to be treated not as an auxiliary instrument but as an integral component of management and marketing strategy.

In this way, the study broadens the understanding of social media as a management tool, showing that its role extends beyond visibility to encompass organizational credibility, knowledge sharing, and relationship building. From a theoretical perspective, the research findings make it possible to gain a deeper understanding of how industry-specific factors influence the effectiveness of communication in social media. They demonstrate that in the case of manufacturing and industrial enterprises, effectiveness should not be assessed through quantitative indicators of activity, but rather through the quality of relationships, reputation, and the level of trust that the organization is able to establish within the digital environment. This indicates that social media serve not only as a promotional channel but also as a tool for building professional image and organizational credibility. The study also shows that short-term phenomena such as sudden increases in popularity or viral effects do not constitute reliable measures of success, as long-term effectiveness in communication results from consistency, coherence, and the alignment of messages with stakeholder expectations. From a practical perspective, the findings emphasize the necessity for manufacturing enterprises to treat social media as a key component of long-term communication and brand development strategy. Effective use of digital channels requires regular activity, the development of analytical competencies, and a coherent narrative tailored to the characteristics of the sector. The best results are achieved by organizations that combine educational and informational content with authentic storytelling while maintaining consistency across communication channels. It is also important to highlight the significance of investing in human and technological resources - the lack of dedicated specialists and analytical tools remains one of the main limitations to the effective use of social media. The results confirm that success in digital communication stems from long-term planning, consistent execution, and data-driven decision-making rather than intuition. Future research should expand the analysis to include financial and temporal dimensions to better understand how social media activity influences business performance, innovation capacity, and the sustainable growth of organizations.

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GRADUATE CAREER TRACKING SYSTEMS OF HIGHER EDUCATION INSTITUTIONS – A SYSTEMATIC LITERATURE REVIEW

Małgorzata CIECIORA[1*], Wiktor BOŁKUNOW[2], Piotr PIETRZAK[3], Agnieszka KUCHARSKA[4]

[1] Faculty of Information Management, Polish-Japanese Academy of Information Technology, Warsaw, Poland; Malgorzata.Cieciora@pja.edu.pl, ORCID: 0000-0002-4161-4653
[2] Collegium of Management and Finance, Warsaw School of Economics, Warsaw, Poland; wbolk@sgh.edu.pl, ORCID: 0000-0002-1480-1031
[3] Management Institute, Warsaw University of Life Sciences, Warsaw, Poland; piotr_pietrzak1@sggw.edu.pl, ORCID: 0000-0002-1319-4815
[4] Faculty of Management, Warsaw University of Technology, Warsaw, Poland; Agnieszka.Kucharska@pw.edu.pl, ORCID: 0000-0002-2389-2369
* Correspondence author

Purpose: The aim of the present paper is twofold: firstly, to provide a review of the extant research on systems used by higher education institutions to monitor the professional careers of their graduates, and, secondly, to identify gaps in the current body of knowledge in this field.
Design/methodology/approach: The study employed the systematic review methodology. It consists of a review of thirty-one refereed articles on graduate career tracking systems derived from the Scopus database.
Findings: Four predominant areas of research have been recognized: (1) a rising trend in the computerization of graduate tracking systems, (2) a common use of surveys, (3) a gradual progression towards centralized systems, and (4) a growing prevalence of hybrid systems. The main finding of the research is that a comprehensive system for monitoring graduate employability is still to be established. However, it is important to acknowledge the development of effective systems for tracking graduates in the medical field.
Research limitations/implications: The scope of the study was limited by the parameters of the selected Scopus database and the predefined search criteria.
Practical implications: The findings may prove useful in the development of graduate career tracking systems in higher education institutions worldwide.
Social implications: Acquiring insightful feedback on educational outcomes can help higher education institutions better organize their studies, update their curricula, and modernize their teaching strategies in order to successfully meet the rapidly shifting demands of society.
Originality/value: The study has contributed to the expanding corpus of knowledge on graduate employability and proposed venues for future research. It has presented an array of graduate career tracking tools that are being used and can be benchmarked, as well as signaled the main challenges connected with their implementation.
Keywords: higher education; graduate career tracking system; employability; systematic literature review; Scopus.
Category of the paper: Literature review.

1. Introduction

Since their medieval beginnings, higher education institutions have played many important societal roles. As Sporn and Godonoga (2024) noticed, they "have responded to various societal demands, from reproducing religious administrators and educating elites to manage trade, to developing economically useful knowledge and supporting democracy" (Sporn. Godonoga, 2024, p. 1). Their missions and organization of studies have been subject to changes, following the changes in their environments. Thus, in the Medieval Ages, the first European universities – Bologna and Paris – concentrated on the preservation and teaching of the existing knowledge, with the focus on the art of conducting theoretical disputes in Latin. In contrast, in the 19th-century preindustrial German states, at the University of Berlin, original research became academicians' main point of interest, later integrated with classroom teaching at Humboldtian German universities. And in the second half of the 19th century, American universities developed the idea of the "public service mission", i.e., service to the public of the nation-state being one of the main tasks of higher education institutions. It was understood as providing useful knowledge and academic research to society. One of the consequences of adopting this mission was the establishment of a new type of universities and colleges, namely institutions that specialized in teaching agricultural engineering and mechanics (e.g., Massachusetts Institute of Technology) rather than conducting basic research (Matusiak, 2010; Scott, 2006). Thus, one can conclude that throughout the ages, higher education institutions have gradually shifted the focus from being purely "temples of knowledge" to becoming active partners for government, business, and industry.

Nowadays, the tasks of higher education institutions are even more complex, and the societal demands they are supposed to meet are on the increase. As defined by UNESCO (United Nations Educational, Scientific and Cultural Organization), higher education "is a rich cultural and scientific asset which enables personal development and promotes economic, technological and social change. It promotes the exchange of knowledge, research, and innovation, and equips students with the skills needed to meet ever changing labor markets. For students in vulnerable circumstances, it is a passport to economic security and a stable future" (UNESCO, 2025). An important conclusion that can be drawn from the above definition is that one of the main concerns of higher education institutions is the employability of their graduates. In other words, academic decision-makers should organize their educational offer to effectively equip students with the knowledge and skills useful in their future careers, and later obtain reliable and constructive feedback about the real value of their educational outcomes.

These are not easy tasks. First, because the very concept of employability, especially in the context of higher education, has been a much-debated question, and the consensus is far from being reached. Bridgstock and Jackson (2019) identified three main strategic approaches to defining and measuring employability by higher education institutions: (a) short-term graduate

employment outcomes, (b) readiness to enter a profession through professionally accredited degree pathways, and (c) living and working productively and meaningfully across the lifespan. Each of them has its advantages and disadvantages. The first "employability aim" is the most popular one and concentrates on measuring "tangible" key performance indicators for graduate employability, such as the percentages of graduates obtaining full-time jobs and their salary levels, a few months after course completion. It does not, however, take into consideration the information concerning other types of employment, such as project-based or entrepreneurial ways of working, or the long-term professional progress. The second one is based on organizing studies to meet the requirements of external accreditation bodies. This approach is mandatory in "regulated" professions where public safety needs to be ensured, such as medicine; it may also apply to some "non-regulated" professions, e.g., accountancy. Its main advantage is providing the quality and safety ensured by professional standardization, and the main disadvantage consists of lowering the flexibility of the curricula to meet the external standards, and educating students in very narrow specializations, which may limit their future career options. Finally, the third approach is the broadest in meaning, and at the same time, the most difficult to define precisely. Here, employability is „the capacity to employ or use one's capabilities in ways that are personally meaningful and appropriate, and contribute to the contexts with which the graduate interacts" (Bridgstock, Jackson, 2019, p. 474). This approach takes into account the possibility that graduates may have, e.g., other personal goals and needs than merely obtaining a well-paid job soon upon graduation; for some, the priority may be to balance work and non-work activity, and others decide to study just for the sake of learning new knowledge. If one adopts this "employability aim", measuring educational outcomes will be demanding.

The second challenge for academic decision-makers connected with the employability issue is more technical and concerns the establishment and use of ways of obtaining and processing information on the professional fates of graduates. Regardless of which of the strategic employability aims a higher education institution has decided to focus on, it should be able to find out whether it has achieved this aim. And it seems that, though the – much disputed - topic of defining graduate employability has been quite extensively researched, there is still uncertainty about whether higher education institutions have managed to build effective, procedure-based systems of collecting and processing feedback on their educational outcomes, as many researchers point out a phenomenon of competency gap among graduates and lack of working communication channels between the business and academic worlds (Suleman et al., 2021; Arranz et al., 2022; Mohd Noor et al., 2024; Scandurra et al., 2024). This indicates a clear research gap, as little is known about the actual efficiency, scope, and institutionalization of graduate career tracking systems, as well as the challenges higher education institutions face when attempting to assess the long-term value of their educational outcomes.

Therefore, the main objectives of this study are to examine the current state of knowledge on the types of graduate employability tracking methods higher education institutions use now, as well as problems and challenges they encounter during attempts to assess the real value of their educational outcomes. And it is worth emphasizing that acquiring insightful feedback on educational outcomes can significantly help higher education institutions better organize their studies, update their curricula, and modernize their teaching strategies in order to meet the rapidly shifting demands of society successfully. Therefore, the findings of the study should be of interest to both academic decision-makers, as they can help them develop efficient graduate employability tracking systems in their institutions, and researchers, who will be provided with the information on gaps within the research area and directions for future studies. To the best of current knowledge, this appears to be the first review consolidating research objectives, methodologies, and findings in this category into a structured overview.

2. Methods

The authors decided to use the qualitative Systematic Literature Review (SLR) method to analyze the current state-of-the-art knowledge and to identify the gaps in the field of systems of monitoring the employability of graduates of higher education institutions. The SLR method was chosen as it is more formal, rigorous, reproducible, and focused than a standard literature review, whose aim is to provide context for a new piece of research rather than to find specific answers to a 'clinical question' (Tranfield et al., 2003; Carrera-Rivera et al., 2022). Examples of some prominent areas where SLR is commonly utilized include healthcare (e.g., Ungaro et al., 2024), education (e.g., Schildkamp et al., 2020), engineering (e.g., Dasaklis et al., 2022), as well as environmental and agricultural sciences (e.g., Datta et al., 2024).

The authors adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a transparent, structured, and replicable review process. This approach was chosen to clearly document the identification, screening, eligibility, and inclusion stages of the literature selection, allowing readers to understand how the final set of studies was determined and to enhance the methodological rigor of the systematic literature review.

The SLR began with the formulation of three research questions (RQ), which the authors intended to answer in the course of the review:

- RQ1: Which graduate career tracking systems topics are currently well-researched, and which are not?
- RQ2: Which research methods were used in the studies on graduate tracking systems?
- RQ3: What are the main findings concerning the graduate tracking systems?

The three RQs outlined in the SLR were designed to provide a comprehensive, structured understanding of the current state of research on graduate career tracking systems, with both academic and practical relevance. By asking which topics are well-researched and which remain underexplored (RQ1), the authors aimed to identify areas of strength and gaps within the existing body of knowledge. This is particularly important for guiding future academic inquiry and ensuring that institutional and policy-level decisions are grounded in a well-mapped evidence base.

The second question (RQ2), which examines the research methods employed in the reviewed studies, allows for a critical evaluation of how the field is being studied. Understanding the methodological approaches provides insight into the robustness and diversity of existing research and helps identify potential limitations, such as overreliance on specific methods or lack of longitudinal data.

The third question (RQ3) seeks to synthesize the main findings of the literature, offering a clear picture of what is currently known about graduate career tracking systems. This is particularly valuable for higher education institution managers and public policymakers, who can use these findings to inform the development of tracking mechanisms, improve employability strategies, and align educational offerings with labor market needs.

Together, these questions ensure that the review is not only academically rigorous but also practically useful. They reflect a commitment to bridging research with real-world application, offering insights that can enhance institutional decision-making, policy design, and strategic planning in higher education and beyond.

The authors decided to use the Scopus database for the search. The selection of Scopus as the primary repository for this study was largely influenced by its ease of access and comprehensive coverage. In the current landscape of scientific research, online databases have become the dominant means of acquiring scholarly information. Scopus, in particular, encompasses a significant number of high-impact publications pertinent to the research topic. Additionally, Scopus offers a robust and extensive collection of abstracts, making it a favored choice among scholars conducting SLRs, who often cite its reliability and breadth (e.g., Lim et al., 2022).

The data search was carried out on 26 October 2024. The document type was limited to articles, conference papers, book chapters, and the English language within the time limit of the last decade (2014-2024), as in 2014, Pavlin and Svetlik (2014) signaled a lack of efficient graduate employability monitoring systems search was conducted within: Article title, Abstract, Keywords, and the search terms were formulated as: ((‘monitoring’ OR ‘tracking’) AND (‘employability’ OR ‘career’) AND ‘graduate’). Then the authors conducted a supplementary search focused on: (TITLE-ABS-KEY (‘graduate’ AND ‘career’ AND ‘tracking’ AND ‘system’ AND ‘higher’ AND ‘education’) and combined it with the first string. Altogether, they obtained eighty-nine papers, and after scrutiny, they decided to progress thirty-one for further study. The authors determined to study each paper that contained information relevant to the

research questions, even if the issue of graduate employability tracking systems was not specified as the main subject matter of the paper. The articles that were excluded were irrelevant to the main topic of the study or were not written in English. Figure 1 presents the PRISMA diagram used in the study.

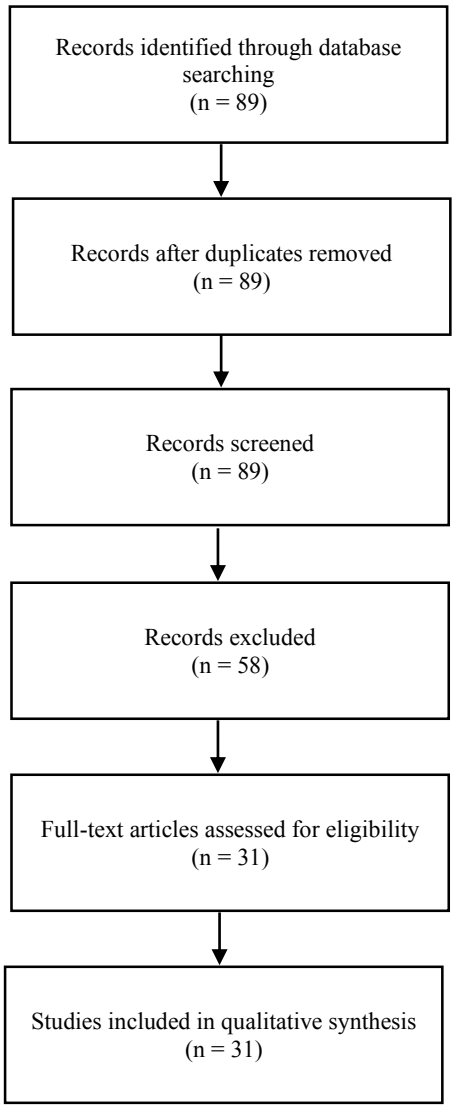


Figure 1. PRISMA diagram of the study.

Source: Own elaboration.

The detailed description of the database selection, search strings, inclusion and exclusion criteria, and PRISMA flow diagram ensures that the process is transparent and replicable. This allows other researchers to reproduce the review or to update it in the future with new studies.

3. Results

The following section presents the main results of the systematic review. The findings are focused on the distribution of studies by type, subject area, and publication form, as well as the qualitative synthesis of their content.

Most of the papers were articles (23) conference papers (6), published mainly within the subject areas of: social sciences (21), computer science (8), business, management and accounting (5), engineering (4), decision sciences (3), health professions (3), mathematics (3), or medicine (3). Only two publications were prepared in the form of book chapters. It is worth noting that these publications were interdisciplinary and represented more than one field of study, which is why their total does not add up to 31.

The qualitative results of the analysis are summarized in Table 1 and discussed in the next chapter.

Table 1.
Literature on Graduate Career Tracking Systems.

Category: Central systems				
Author(s), publication year	**Journal/Conference**	**Research objective(s)**	**Methodology**	**Main contributions/ Findings on graduate career tracking systems (GCTS)**
Kosztyán et al., 2021* * The article contains information also from the IT-supported tools category.	Applied Network Science	To present how to measure the role of higher education institutions in the spatial mobility of their graduates by combining economic and network models.	A statistical analysis of information obtained from the countrywide employability tracking system (HCSTGC) and Central Statistical Office in Hungary, an anonymized student application database, and Eurostat.	There is a possibility to use combined data-driven gravity-like economic models and a mobility network model in measuring graduate employability.
Pavlin, 2019	European Journal of Education	To analyze the current reality of tracking graduates' employability in Europe and to discuss the issues of developing graduate career monitoring system(s), with a focus on Slovenia.	Literature review	A national graduate employability monitoring system should be capable of obtaining and processing data from administrative records and from surveys completed by graduates and employers, taking into consideration possible disciplinary particularities.
Zając et al., 2018	Polish Sociological Review	To analyze the differences in labor outcomes between graduates from public and non-public higher education institutions.	A thorough analysis of data derived from ELA - The Polish Graduate Tracking System.	The Polish Graduate Tracking System should be developed by comprising data from other resources, such as higher education institutions' internal databases which collect data on graduates' study successes. Linking data from a number of registers in Poland should be an easy task, as all those registers use the citizens' unique PESEL (personal identity number) numbers as identifiers.

Cont. table 1.

Pavlin & Svetlik, 2014	International Journal of Manpower	To present an overview of the employability of graduates of European higher education institutions from a global perspective.	Literature review.	With a few exceptions, European higher education institutions have neither built comprehensive graduate employability tracking systems nor are willing to use the information from occasionally conducted surveys to change their curricula.
Category: IT-supported tools				
Author(s), publication year	**Journal/Conference**	**Research objective(s)**	**Methodology**	**Main contributions/ Findings on graduate career tracking systems (GCTS)**
Gonzales et al., 2024	2024 IEEE 15th Control and System Graduate Research Colloquium (ICSGRC).	To create a graduate tracker monitoring platform.	Decision Support System and mapping recommendation analysis using a rule-based algorithm to evaluate the results of alumni program evaluation on five areas: curriculum, faculty, facility, laboratory, and student services.	A prototype of a Graduate has been proposed Tracer Monitoring Platform with Decision Support Feature and Mapping Recommendation Analysis using a Rule-Based Algorithm that would provide Alumni Registration, Employment Records, Program Evaluation, Job-Matching, Tracer, Report Generation, and Content Management System.
Hristova et al., 2023	2023 4th International Conference on Communications, Information, Electronic and Energy Systems (CIEES), Plovdiv, Bulgaria, 2023.	To present a concept of a blockchain tool designed for collecting and processing data on technical competencies gained during both studies and work experience.	Presentation of a blockchain technology model.	There is a possibility to use an automated blockchain instrument for tracking and sharing data on competencies (certificates) earned during both academic training and professional career) – all eligible stakeholders, including employers and universities, could have access to the data inserted.
Sanusi et al., 2023	2023 6th International Conference on Applied Computational Intelligence in Information Systems: Intelligent and Resilient Digital Innovations for Sustainable Living, ACIIS 2023 – Proceedings	To examine the academic and professional progress of graduates at a university in Malaysia.	A mixture of data analysis techniques visualized with a Power BI Dashboard and used to foresee future educational and professional career steps of graduates.	Data analysis techniques and machine learning algorithms may be of assistance in gaining insights into predicting graduate employability.
Pico-Saltos et al., 2021	Sustainability.	To define objective and subjective graduate career success factors.	A statistical analysis of a graduate survey, followed by the development and validation of a graduate career success prediction model built with the use of Waikato Environment for Knowledge Analysis (WEKA).	A survey-based, mathematically validated career success measuring instrument has been proposed.

Cont. table 1.

Scandurra et al., 2024* * The article contains information also from the Constructing, collecting, and analyzing surveys category.	Studies in Higher Education.	To examine the current body of knowledge on employability activities in HEIs aimed at facilitating graduate employability.	Systematic review.	Higher education institutions should conduct more empirical research on their graduates' employability instead of focusing only on the projected benefits of their Work-Related Learning programs.
Tecilazić et al., 2024* * The article also contains information from the Constructing, collecting, and analyzing surveys category.	Education Sciences.	To examine the influence of approaches to learning on career readiness and social/entrepreneurial skills of graduates in Austria, Croatia, Czechia, Lithuania, Malta, and Norway.	A pilot graduate survey launched by the European Commission.	Further studies are required to analyze the characteristic features of higher education systems and the cultural aspects of learning and teaching in various countries.
Courtial, Garrouste, 2014	Proceedings of the 19th World Congress The International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014	To equip universities in France with an instrument capable of matching their graduates' competencies with the European labor market demand, focusing on Earth Sciences.	Building a new model of forecasting graduate employability – a combination of predictive control and econometric models.	There is a possibility to use a sophisticated computer-assisted model to predict and measure the employability of graduates.
Articles that contain information from the IT-supported tools category that have been presented in another category: Kosztyán et al., 2021 (the Central systems category).				
Categories: **Countrywide and cross-national surveys and surveys of individual higher education institutions** **Constructing, collecting, and analyzing surveys*** ***The articles in the two categories have been grouped as a vast majority of them overlap and contain valuable information concerning both topics.**				
Author(s), publication Year	**Journal/Conference**	**Research objective(s)**	**Methodology**	**Main contributions/ Findings on graduate career tracking systems (GCTS)**
Tseng et al., 2024* * The article also contains information from the Personal Data Protection Category.	Studies in Higher Education.	To analyze the impact of long-term interdisciplinary learning on graduates' employability in Taiwan.	Analysis of data from National Tsing Hua University in Taiwan (NTHU) administrative records, graduate surveys and employability data obtained from the Ministry of Education in Taiwan.	There has been proposed a model that integrates internal administrative data of a higher education institution with the information from the (high response) Graduation Survey and employability data obtained from the Ministry of Education.
Mohd Noor et al., 2024	International Journal of Evaluation and Research in Education.	To diagnose personal and technical competencies important for employability in the Malaysian electrical and electronic industry.	Statistical analysis (t-test) on an online structured questionnaire survey completed by representatives of higher education institutions and the industry.	There has been presented a description of the authors' own survey on graduates' soft and hard skills.

Cont. table 1.

Connell et al., 2023	BMC Medical Education.	To evaluate the impact of participant non-response rates on career tracking studies of medical school graduates in New Zealand.	A statistical analysis of demographic variables of medical graduates in New Zealand.	There are significant differences in response rates and representativeness of survey results depending on the type of survey – (highly representative) entry and exit surveys versus (under-representative) post-graduation survey.
Reinhardt et al., 2023	Journal of Dental Education.	To analyze demographic data of dentistry graduates of a university in Nebraska and factors that influenced their rural or urban practice site choices in a 10-year long span.	A statistical analysis of data obtained from a survey conducted by the Health's Health Professions Tracking Service (HPTS) and the internal data of the dentistry college.	The data obtained annually by the survey is verified and updated by HPTS, which acquires and processes information from state licensure and Postal Service records, the media, and obituaries. In case of questions about practice locations, HPTS contacts the practices directly.
Acero et al., 2023	Proceedings of the 7th Brazilian Technology Symposium (BTSym'21). BTSym 2021. Smart Innovation, Systems and Technologies.	To analyze the graduate employability tracking programs developed by higher education institutions in Peru.	A statistical analysis of data on graduate monitoring and labor insertion programs.	Higher education institutions should have and regularly update databases of their students and graduates – they would serve as an essential tool for graduate employability tracking.
Comunian et al., 2023	Arts and Humanities in Higher Education.	To analyze the employability of graduates of Arts & Humanities in comparison to graduates of other fields of study in Europe.	An analysis of the pilot Eurograduate survey conducted in 2018.	The response rate of the pilot European Graduate Study conducted in eight countries and sent to over sixteen thousand graduates was only 12 per cent.
Jackson, Li, 2022	International Journal of Manpower.	To analyze how factors determining graduate employability change over time.	A statistical analysis of data on over forty thousand graduates of Australian universities surveyed twice - after 4 months and then after 3 years following their graduation.	Graduate Employability Tracking systems should also analyze longer-term outcomes.
Pico-Saltos et al., 2022	Applied Sciences.	To develop a graduate career success prediction model.	A statistical analysis of a graduate survey followed by the development and validation of a graduate career success prediction model based on a genetic algorithm.	The graduate employability monitoring system should measure objective and subjective success factors and take into consideration the business environment. HEIs should also try to establish and foster both formal and informal communication with professionals.
Arranz et al., 2022	Studies in Higher Education.	To analyze the impact of the university-business cooperation on the employability of students.	A statistical analysis of the information obtained from a telephone survey organized by the European Commission in thirty-one countries, which collected responses from over seven thousand companies.	Enterprises with a higher degree of satisfaction with the employability of graduates develop a wide array of cooperation channels with higher education institutions, especially internship programs.

Cont. table 1.

Hynninen et al., 2022	UKICER '22: Proceedings of the 2022 Conference on United Kingdom & Ireland Computing Education Research.	To analyze recommendations obtained from graduates concerning key skills and competencies needed in the information technology industry.	A statistical analysis of a countrywide graduate survey completed five years after graduation.	Information obtained from employability tracking surveys on recent graduates can be a valuable indicator of the efficacy of the educational program in preparing graduates for the industry.
Sutton et al., 2021	Rural and Remote Health.	To research the practice intentions of graduates of nursing and allied health fields of study in Australia.	An analysis of the Nursing and Allied Health Graduate Outcomes Tracking (NAHGOT) study.	The graduate employability tracking model should combine many variables, such as demographics, educational and professional accomplishments as well as changes in career and life priorities.
Zhang et al., 2021	BMC Medical Education.	To research the quality of clinical training of recent MD graduates in China.	Analysis of a graduate online survey.	Respondents received financial remuneration for completing the survey.
Gatt et.al., 2021	Teaching and Learning: Symposium.	To analyze the employability of graduates of the political science field of study in Austria.	Analysis of data obtained from the Graduate Monitoring system and interviews with university graduates.	Scholars (of political science) tend to assess the importance and value of studies only from the academic point of view and lack empirical evidence and information on the influence of learning outcomes on the professional careers of their graduates.
Balogh, Sipos, 2020	International Journal of Educational Management.	To analyze possible differences in employability between graduates who did and did not change their field of study while making the second-degree study choices, focusing on Hungarian HEIs.	Analysis of employability data of three groups: generalists, specialists, and field changers. The data was taken from the Hungarian central systems and an individual higher education institution' internal administrative records.	One can obtain valuable data on graduates' salaries (correlated to such variables as the degrees obtained) from countrywide sources such as the Graduate Career Tracking System and the higher education institution specific Integrated Administrative Databases.
Jackson, Bridgstock, 2018	Higher Education Research & Development.	To summarize and critique ways of measuring graduate employability.	A literature review critical analysis of tools of tracking and measuring graduate employability (with the focus on graduate tracking surveys, specifically in Australia).	There is a need for a more nuanced approach to measuring employability outcomes that would take into account other factors apart from (overeliant) full-time employment figures, such as socio-cultural and economic values.
Larkins et al., 2018	BMC Medical Education.	To analyze correlations between various demographic variables and the practice choices of entry and exit groups of students at medical schools.	A statistical analysis of a survey-based study conducted in six countries.	The graduate employability study is based on a series of surveys conducted first at the beginning of medical studies and then a few times after graduation.
Burnasheva et. al., 2016	2016 IEEE V Forum Strategic Partnership of Universities and Enterprises of Hi-Tech Branches (Science. Education. Innovations).	To discuss existing solutions used in graduate employability tracking and present a new efficient model that can be used by universities in Russia.	An analysis of data from the ministerial databases, especially from the Pension Fund and the data obtained from the higher education institution' internal graduate survey.	The central graduate employability tracking system based on data from the Pension Fund is the most objective, but its main disadvantage is a significant time lag in providing the data to other stakeholders.

Cont. table 1.

Woolley et al., 2015	Rural and Remote Health.	To evaluate the performance of regional medical schools in Australia.	An analysis of a medical school graduate tracking system in Australia.	An efficient graduate tracking system consists of exit surveys, a Facebook page that can be used to access graduates more efficiently than by email, and data from the website of the National Health Practitioner Regulation Agency.
Weller et al., 2015	Journal of Food Science Education.	To assess the effectiveness of studies conducted at a university in the United States in the field of food science.	An analysis of an online alumni survey and companies' websites.	The comprehensive graduate employability analysis comprised data obtained from alumni surveys, their employers' websites, and the university's internal records.
Articles that contain information from the Constructing, collecting, and analyzing surveys category that have been presented in another category: Scandurra et al., 2024, Tecilazić et al., 2024 (the IT-supported systems category).				
Category: Personal Data Protection				
Author(s), publication year	**Journal/Conference**	**Research objective(s)**	**Methodology**	**Main contributions/ Findings on graduate career tracking systems (GCTS)**
Proteasa, Vertes-Olteanu, 2022	In: Curaj, A., Salmi, J., Hâj, C.M. (eds) Higher Education in Romania: Overcoming Challenges and Embracing Opportunities	To research the challenges connected with the development of institutional graduate employability tracking systems and data protection legislation.	Analysis of two case studies: Sweden and Romania.	Proper legislative and coding solutions can help to overcome the problem of personal data protection in graduate tracking systems.
Articles that contain information from the Personal Data Protection category that have been presented in another category: Tseng et al., 2024 (*the Countrywide and cross-national surveys and surveys of individual higher education institutions, and Constructing, collecting, and analyzing surveys categories*).				

Source: Own elaboration based on the literature review.

The studies examined graduate employability and career outcomes, evaluated institutional tracking systems and monitoring tools, and developed models or frameworks for assessing competencies, skills, and career success. They also analyzed influencing factors such as education, learning approaches, demographics, and institutional practices, as well as reporting on methodological challenges and system development issues.

Methodologies included statistical analyses of large administrative and survey datasets, literature and systematic reviews, pilot surveys, case studies and interviews, and the development and validation of predictive and decision-support models. Additional approaches comprised rule-based mapping, visualization and dashboard implementations, and computational techniques such as econometric, machine-learning, and genetic-algorithm methods.

Reported contributions on GCTS included the integration of administrative, institutional, and survey data; the application of models (economic, mobility, ML, blockchain) for measurement and prediction; observations on response-rate and representativeness issues; the measurement of both objective and subjective outcomes in short- and long-term perspectives; and references to employer engagement, legal safeguards, and data linkage. The next chapter presents a discussion of these findings.

4. Discussion

The review shows that there have been numerous studies to investigate the following main topics: computerized employability tracking and analyzing systems, survey/interview-based tracking systems, nationwide/international systematized tracking systems, individual academy-to-graduate feedback collecting systems, and combinations of the above; some of the topics overlap.

4.1. Central systems

Some studies presented frameworks of country-central employability monitoring systems, e.g., ELA (Polish Graduate Tracking System) in Poland (Zając et al., 2018). Most researchers seem to be critical of the slow development of such systems. Kosztyán et al. (2021) remarked that currently, there are very few central graduate tracking systems (Hungary, Estonia and Italy being noticeable exceptions), such as the Hungarian HCSTGC (Hungarian central system for tracking graduates' careers), which includes anonymized information on the location of residence (the region), the city (or subregion) of the higher education institution, the county and subregion of the workplace, and starting salary of all graduated employees. They called for establishing such a system at the European Union level (or higher). A similar observation was made by Pavlin (2019), who stressed the need to develop comprehensive national graduate employability tracking systems. As he noticed, 'Yet the typical graduate in most EU countries currently has very limited reliable information on which career paths normally follow particular higher education programs, whilst academics are not sure if more practical-based ways of teaching and learning truly contribute to better career development. Very few understand the complex transition from education to the labor market' (Pavlin, 2019, p. 262). It seems that the situation in Europe has not improved significantly since 2014, when Pavlin and Svetlik remarked that, 'With some exceptions, higher education institutions in Europe still do not have comparative systematic systems in place to trace their graduates from education to the labor market. In general, they have neither the knowledge nor the motivation to transfer the results gained from occasional surveys into their curricular practices' (Pavlin, Svetlik, 2014, pp. 422-423).

4.2. IT-supported tools

A significant number of studies focused on the construction and use of various IT-supported graduate tracer monitoring platforms. Thus, Gonzales et al. (2024) presented a Decision Support System and mapping recommendation analysis using a rule-based algorithm to evaluate the results of alumni program evaluation on curriculum, faculty, facility, laboratory, and student services. Hristova et al. (2024) discussed the possible uses of an automated blockchain instrument for tracking and sharing data on competencies acquired by graduates

during both studies and professional careers. A Power Business Intelligence Dashboard-based combination of data analytics techniques and machine learning algorithms was created to predict graduate employability in Malaysia (Sanusi et al., 2023). Courtial and Garrouste (2014) presented a model combining an econometric model of employability and a predictive control approach to measure graduate employability in France. Pico-Saltos et al. (2021, 2022) came up with a prediction model of alum career success based on the use of a genetic algorithm that was used in Ecuador, and Kosztyán et al. (2021) proposed a model that combined gravity-like economic models and a mobility network model to measure graduate employability in Hungary.

4.3. Countrywide and cross-national surveys and surveys of individual higher education institutions

Most research discussed survey-based instruments of employability tracking, either mentioning them as a part of a general framework or concentrating on their technical form. Graduate employability tracking systems can be broadly divided into two parts: countrywide, or cross-national surveys, such as the Eurograduate Pilot Survey launched by the European Commission in eight EU countries in 2018 (Comunian et al., 2023; Tecilazić et al., 2024), 'Employers' perception of graduate employability' study by Flash Eurobarometer, coordinated by the European Commission, which covered the 27 EU Member States, Norway, Iceland, Croatia, and Turkey in 2011 (Arranz et al., 2022), Nursing and Allied Health Graduate Outcomes Tracking study and the Graduate Outcomes Survey (GOS) in Australia (Jackson, Bridgstock, 2018; Sutton et al., 2021; Jackson, Li, 2022), the Destinations of Leavers from Higher Education (DLHE) in the United Kingdom (Jackson, Bridgstock, 2018), The Medical Schools Outcomes Database and Longitudinal Tracking Project (MSOD) in New Zealand (Connell et al., 2023), the THEnet Graduate Outcome Study (GOS) conducted in Australia, Belgium, Sudan, Philippines, Canada, and South Africa, (Larkins et al., 2018), Finland (Hynninen et al., 2022), and China (Zhang et al., 2021), and surveys conducted by individual higher education institutions, e.g. in Malaysia (Mohd Noor et al., 2024), Ecuador (Pico-Saltos et al., 2021, 2022), Peru (Acero et al., 2023), and the USA (Weller et al., 2015; Reinhardt et al., 2023). Jackson and Bridgstock (2018) produced a general description of several central graduate employability tracking systems, e.g., in Australia, New Zealand, the USA, and Europe. They noticed the growing need and popularity of searching for longitudinal data on graduate outcomes. Some of the studies described models that are based on a combination of data from countrywide registrars and surveys commissioned by individual higher education institutions, e.g. in Austria (Gatt et al., 2021), Taiwan (Tseng et al, 2024), Russia (Burnasheva et al., 2016), Hungary (Balogh, Sipos, 2020) or Australia (Woolley et al., 2015). Weller (2015) presented an interesting model that used information from internal university data (e.g. the class size or Graduate Record Examination scores of students) and information obtained directly from graduates concerning the classification of employment by industry and job title that, in turn, should be checked against information obtained from each company's website.

4.4. Constructing, collecting, and analyzing surveys

As it has been already mentioned, several studies gave insight into the surveys' technical form, e.g. the type of questions, and /or measures and control variables (Gatt et al., 2021; Zhang et al., 2021; Arranz et al., 2022; Hynninen et al., 2022; Jackson, Li, 2022; Comunian et al., 2023), specific variables of 'the recruitment and data collection process at each stage, from university admission, undergraduate attendance at university and after graduation' (Sutton et al., 2021), details of the admission and undergraduate data, e.g. student identification number, hometown at application to the higher education institution, date of birth, gender, ethnicity, interview score, Tertiary Entrance Score (an Australian rank – ordered, school-leaving), then Honors (if awarded) or placement locations in Years 2, 4 and 6 (Woolley et al., 2015), variables used in the Medical Schools Outcomes Database (MSOD) survey-based national project in Australia and New Zealand, which included even data generally considered highly sensitive, such as ethnic identity and relationship status (Connell et al., 2023), variables used in the Eurograduate Pilot Survey, which concerned, among others, lectures, group assignments, internships and work placement, teacher being 'the main source of information, project- and/or problem-based learning', 'extra work above exam requirements', 'non-study-related work experience in the country of studies', 'non-study-related work experience abroad', or 'labour market experience before study program (at least 6 months)' (Tecilazić et al., 2024). Tseng (2024) presented detailed variables of an integrated model made to measure 'the influence of interdisciplinary learning on post-graduation plan choices' based on data from the university's internal administrative records, graduation surveys, and career-tracking data obtained from the Ministry of Education. Mohd Noor et al. (2024) introduced their own survey designed to analyze the soft and hard skills of graduates. Also, Pico-Saltos et al. (2021) discussed an array of objective and subjective career success variables used in their model, distributed in three levels: successful, moderately successful, and unsuccessful. As far as the issue of survey responsiveness is concerned, Connell et al. (2023) noticed the differences in survey representativeness between (highly representative) entry and exit surveys versus (under-representative) post-graduation surveys. Hynninen et al. (2022), in turn, observed that one should be aware of a selection bias in graduate employability surveys, as less professionally successful graduates may not be as willing to complete the surveys as their more successful colleagues. An interesting solution aimed at increasing the survey response rate was presented by Zhang et al. (2021), who mentioned that medical school graduates who took part in the study received compensation in the form of ¥10.00 on the website.

Despite the problem of decreasing survey responsiveness over time, several authors (Jackson, Bridgstock, 2018; Larkins et al., 2018; Sutton et al., 2021; Jackson, Li, 2022) stressed the need to continue tracking down graduates' professional careers not only upon their graduation but also later, to find out how factors change over time. Sutton et al. (2021), for example, recommended building a comprehensive graduate employability model that would

include a considerable number of variables, among them changes in values and aspirations that may evolve over time. Therefore, cohorts of students-graduates should be surveyed during studies, then each year for 10 years after graduation. That came quite in line with the methodology presented by Larkins et al. (2018) based on a number of surveys conducted first with entering medical students, then at their exit from medical school, next at postgraduate years 1, 4, 7, and finally 10 years after graduation. Jackson and Bridgstock (2018) found out that skills, personal characteristics, and degree-related factors mattered most in the initial career stage, whereas in the medium-term, discipline was more important. They also recommended using not only objective, hard data, such as full-time job salary figures of graduates, but also more nuanced subjective indicators, such as social and economic value, career satisfaction, and graduates' well-being. They, however, noticed problems with reaching out for standardized and comparable data on employability as a number of successful graduates, e.g. of such disciplines as the arts, choose to remain self-employed or part-time employed rather than seek a full-time job and pointed out the need to use social media and professional networking platforms, such as LinkedIn to study and analyze graduate employability outcomes. A similar observation was made by Woolley et al. (2015), who concluded that an efficient graduate tracking system should include the following elements, apart from data from a public regulatory body: an exit survey conducted immediately before graduation (it should also be used to collect each graduate's details and consent to be contacted later to obtain the employability data), and a Facebook page to be able to access even the hard-to-trace graduates, as using Facebook is more efficient and effective in contacting graduates than more traditional phone books, or emails. The data should be stored in a longitudinal tracking database by the higher education institution. Also, Acero et al. (2023) signaled the need to keep and manage updated databases of students and graduates in order to be able to track their employability.

Weller et al. (2015), in turn, pointed out problems with surveying employers of graduates connected with identifying and contacting direct supervisors of the graduates and language barriers present in the case of international employment of graduates. Due to these challenges, researchers have to rely on information concerning students' salaries at their first job following graduation and current job titles of graduates as indirect measures of employer satisfaction. Nevertheless, the information obtained from employers would be very valuable, as Scandurra et al. (2024) recognized the need for more empirical research on the graduate labor market outcomes of higher education institutions and noticed that most studies follow a simple qualitative research design based on a limited amount of interviews (sometimes accompanied by surveys) with students, representatives of higher education institutions, but less frequently with the graduates' employers.

4.5. Personal Data Protection

Proteasa and Vertes-Olteanu (2022) pointed out another problem: personal data protection in European Union legislation. They analyzed, on the basis of two case studies, Romania and Sweden, questions connected with building a comprehensive graduate mobility tracking system that would combine and analyze information from two key sources of different kinds, i.e., administrative data and surveys. They pointed out at the following problems arising during the construction process: creating and storing the administrative, or registry data in different databases and by different entities, difficulties in linking the data sources and processing information due to the personal data protection legislation, and lack of important personal details in the registry data, as some of them can be collected only during more personal contacts, such as interviews. They recommended creating and applying algorithms for computing indicators to the law-protected data to de-identify the microdata, thus making it possible to allow analysts to access electronic platforms with comprehensive, objective, up-to-date, and accurate statistical information on graduate employability on national and European levels. The same research challenge is present in Taiwan, where, as Tseng (2024) noticed, privacy and personal data protection laws prevent researchers from obtaining individual records for the analysis – they only have access to program-level career-tracking data.

5. Conclusions

This paper has reviewed thirty-one Scopus-indexed research papers that contained information on higher education institutions' systems of tracking down the employability of their graduates to find answers to questions concerning the state of the existing body of knowledge, the remaining gaps, methods used in the studies, and their main findings. To address the first research question (RQ1), the literature review has identified four main areas that were addressed and discussed in the literature on the subject: an increasing computerization of the systems, a wide use of surveys in collecting and analyzing data, a (gradual) development of nationwide/international systems, and a rising trend of building hybrid systems that combine information from different sources by individual HEIs. The second research question (RQ2) focused on the methods used in the studies. The articles used literature review methodologies, survey-based instruments, statistical analyses, and presentations of information technology solutions. Quite interestingly, some of the articles (e.g., Reinhardt et al., 2023; Comunian et al., 2023; Gatt et al., 2021) analyzed, though they contained valuable information on graduate career tracking systems, defined other topics as their primary research questions, e.g., they strove to analyze the situation on the labor market of specific groups of graduates,

and the information on graduate employability tracking systems seemed to be a kind of by-product of their research.

The third research question (RQ3) explored the main findings concerning the issue of graduate career tracking systems. The most important conclusion of the study is that a fully informative, reliable system of tracking down graduate professional careers has not been developed yet. Big, centralized systems use objective data from reliable national registrars such as pension funds, but cannot, because of data protection legislation, provide higher education institutions with detailed information on individual graduates. Moreover, they publish the results of their analyses with a significant time delay and do not usually capture information on other forms of employment than full-time jobs. Individual higher education institutions, in turn, though they increased their efforts to establish some graduate tracking procedures, are still struggling to find effective ways of collecting sufficient amounts of reliable data from graduates and their employers on a regular basis. Quite interestingly, there is one group of graduates whose professional careers can be monitored smoothly. This exception to the rule is graduates of some medical fields, as it is relatively easy to find up-to-date information on their employment in widely accessible institutional repositories. Most higher education institutions, however, have to rely on surveys (supplemented by interviews and information from internal and external administrative registrars), whose responsiveness is far from satisfactory and diminishing over time. It is the time factor that seems to be a topic of increasing importance for researchers, as some of them noticed that factors determining graduate employability may change over time. It should also be stressed here that there is an ongoing discussion concerning the type of information on employability that is worth searching for, as some researchers tend to rely on income-based data for measuring professional success, whereas others also value non-financial factors, such as career satisfaction or well-being.

Several questions regarding the development of the internal parts of graduate employability tracking systems of individual higher education institutions remain to be addressed. First of all, though there are many detailed descriptions of questions and variables used in surveys, far too little attention has been paid to the existence in higher education institutions of (or a lack of thereof) procedures and tools designed to analyze and use the obtained feedback in decision-making concerning changes in the curricula, teaching methods, or staff selection. In other words, there is very little scientific understanding of the academic mechanisms of examining the graduate employability data (e.g., whether the survey results are studied regularly by a standing committee or randomly, by the dean, which data, connected with financial or non-financial factors, is given priority, etc.) or the way it may impact the quality of studies of the next cohorts of students (e.g., by introducing the procedure of automatic revision of the curriculum of a given study program in case of obtaining unsatisfactory information concerning the employment rates of its graduates). Moreover, as far as the channels of collecting information on the professional careers of graduates are concerned, very little attention has been paid so far to the role of social media, such as Facebook and LinkedIn. There is little available

literature on the topic of organizing alumni clubs that can serve as a valuable source of information on graduate careers, either. Moreover, only one study mentioned an example of rewarding the graduates for their time and effort devoted to completing surveys, and there were no attempts to investigate factors that would effectively motivate employers to provide feedback on their employees to their Alma Maters. These are important issues for future research.

As far as information technology solutions, such as decision support systems, Business Intelligence tools, or blockchain technologies are concerned, they seem, because of their novelty, to be still in the early stage of development, but certainly pose another important and promising path for future research.

While providing some valuable insight into the topic of tracking down graduate employability, the study is not without limitations. Its scope was limited in terms of the selected database and the defined search criteria. Although Scopus is a widely recognized search platform, one should be aware of the existence of other databases, such as Google Scholar, that store articles from journals, which, though not indexed in Scopus, may be of value. Furthermore, there is a possibility that a number of articles that did not meet the inclusion criteria, e.g., the defined keywords, do contain relevant information on the topic in question.

In addition, certain methodological imbalances across the reviewed studies should be acknowledged. A considerable proportion of the included studies relied on survey-based approaches, which may limit the generalizability of their findings due to response-rate and representativeness issues. At the same time, longitudinal research designs were relatively underrepresented, restricting the possibility of assessing graduates' career outcomes over longer time horizons. Integrating graduate career tracking systems with professional networking sites (e.g., LinkedIn) can enable continuous and passive monitoring of career trajectories, reducing reliance on survey responses. Automatically updated profiles improve data timeliness and accuracy, while aggregated analytics reveal mobility patterns and skill demands. Engagement campaigns via social platforms may increase alum participation, though strict safeguards and transparent governance remain essential for compliance with data protection regulations.

Despite these limitations, the authors believe that the present study has added to the growing body of knowledge on graduate employability and suggested venues for future research.

Most importantly, the insights gained from this research may be of assistance to higher education decision-makers in their attempts to build efficient graduate career tracking systems, as the study has presented an array of graduate career tracking tools that are being used and can be benchmarked, as well as it has signaled the main problems connected with their implementation. And, though as the study has highlighted, there are many challenges with the development of graduate employability tracking systems, including strategic, legal, technical, and procedural issues, higher education institutions will benefit from undertaking the effort, as obtaining reliable, valuable feedback on their educational outcomes can help them develop

and revise curricula, modernize teaching methods, and improve organization of studies to be able to respond successfully to the dynamically changing societal demands.

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CLIMATE IMPACT ON WATER DEPTH AS KEY FACTOR DETERMINING NAVIGABILITY OF THE INLAND WATERWAY

Ernest CZERMAŃSKI[1*], Ryszard ROLBIECKI[2]

[1] Uniwersytet Gdański; ernest.czermanski@ug.edu.pl, ORCID: 0000-0002-2114-8093
[2] Uniwersytet Gdański; ryszard.rolbiecki@ug.edu.pl, ORCID: 0000-0002-6964-8759
* Corresponding author

Purpose: The navigability of inland waterways is critically dependent on maintaining sufficient water depth, which directly determines vessel loading capacity and transport costs. Increasingly frequent and severe climatic variability threatens the reliability of guaranteed depths on key European rivers. This study investigates the relationship between weather conditions and the number of days with reduced navigable depth. The central hypothesis is that climate-related anomalies significantly influence waterway depths and contribute to an upward trend in the number of days during which minimum guaranteed depths are not maintained within the navigation season.
Design/methodology/approach: The analysis focuses on the Rhine and Danube. Data from the Central Commission for Navigation on the Rhine were used, covering the period 2015-2023. The dataset includes the number of days in which required depths were not achieved at selected water gauges, including critical bottleneck locations. To test the research hypothesis, repeated-measures analysis of variance using Friedman ranks was applied. Where incomplete datasets were identified, regression imputation was used to ensure robustness.
Findings: Results confirm a significant impact of weather anomalies on the frequency of days with insufficient navigable depths along both rivers. For the Rhine, a statistically significant upward trend was identified, indicating a growing number of days with depths below guaranteed thresholds. In contrast, no significant upward trend was observed on the Danube, although depth deficiencies remain an operational challenge. The study further demonstrates that reduced guaranteed depths directly constrain inland waterway transport activity and intensification.
Research limitations/implications: The main limitation relates to data gaps in the lower Danube segment, addressed through imputation methods. Despite this, findings provide robust evidence of climate-induced disruptions to navigability. The results highlight the need for waterway authorities to adapt infrastructure and management strategies to ensure reliability under changing climatic conditions.
Originality/value: This article offers original empirical evidence of the climate–navigability nexus in European inland waterways. By quantifying the link between extreme weather events and guaranteed depths, it provides valuable insights for policymakers, river commissions, and infrastructure managers. The findings serve as both a warning and a foundation for future research, while supporting the case for modernisation of waterways and the elimination of bottlenecks to safeguard sustainable inland transport.

Keywords: climate change, inland waterway transport, guaranteed depth of the waterway, barge loading factor.
Category of the paper: Research paper.

1. Introduction

The changes in the role of inland waterway transport in the transport system currently observed in Europe are not in line with the intermodal shift proposed in the White Paper on Transport and the 'Strategy for sustainable and intelligent mobility – European transport on the road to the future' (Fig. 1). In the EU-27 countries, between 2015 and 2023, transport performance in this transport mode decreased from 145.7 billion tkm to 116.4 billion tkm, and the share of this branch in the transport system fell from 6.9% to 5.1% in 2022 and 5,0% in 2023 (Eurostat, 2025a, 2025b). This was the lowest share since 2005.

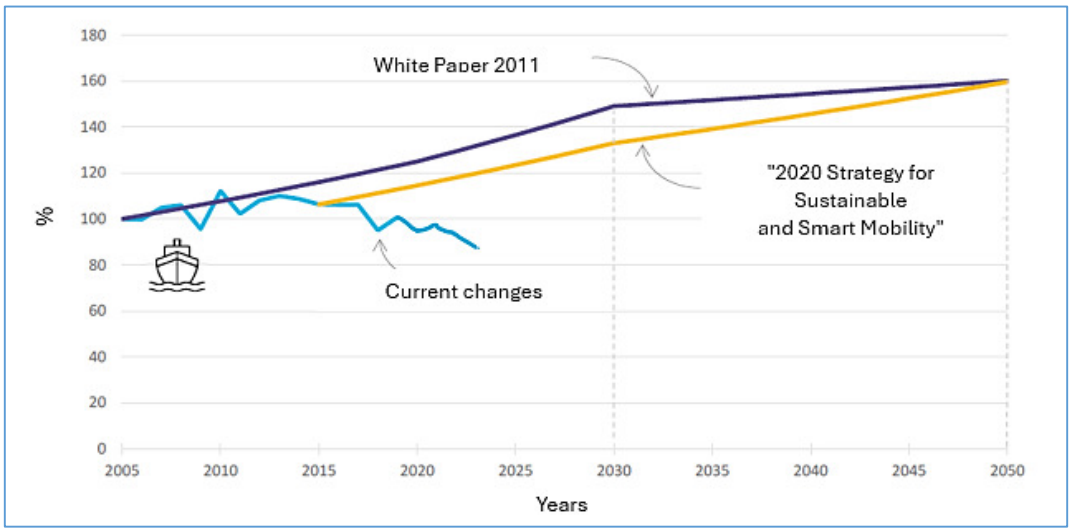


Figure 1. Comparison of inland waterway transport targets with actual transport performance (2005 = 100).

Source: Europäischer Rechnungshof 2023; Eurostat 2019, 2025b.

In order to reverse this unfavourable trend, it is necessary, among other things, to increase or at least maintain the existing capacity of inland waterways. The basic parameter determining the capacity of a waterway is its navigable depth[1] . The depth determines the size of the vessels

[1] Navigable depth in inland navigation is defined as:
- the minimum transit depth, i.e. the minimum depth of a waterway on a specific waterway or section thereof during the navigation season,
- guaranteed depth, i.e. the minimum transit depth with a specified percentage guarantee of its maintenance (for freely flowing European rivers, the degree of guarantee is 85-95%),
- maximum depth, i.e. the greatest depth on a specific waterway at which navigation can still be carried out due to limited clearance under bridges,
- average navigable depth, meaning the average draught of a vessel during the navigation season plus the required safety margin (Kulczyk, Winter, 2003).

that can be operated and the permissible draught of a ship. It is therefore a factor that directly affects the efficiency of inland waterway transport and the profitability of shipping operations (Stanisławczyk, 2005). The depth of the fairway determines the loading level of barges and, consequently, the unit transport costs (Van Dorsser, 2015; Vinke et al., 2022). The significant impact of the depth of the fairway, and consequently the draught of the barge, on the efficiency of inland navigation results from the slower increase in fuel consumption costs than the benefits associated with the increase in load capacity (Kulczyk, Winter, 2003). An increase in draught of 1 cm, for example in the case of a motor barge with a tonnage of 2,350 tonnes and dimensions L = 85, B = 11.45, T = 2.64, means an increase in the load on board by an average of 90 tonnes (Meetbrief voor Binnenvaartuigen, 2001). A reduction in the number of days with low water levels therefore has specific financial implications (Christodoulou, Christidis, Bisselink, 2020).

There is still a trend towards an increase in the average size of ships. The operating costs of large tonnage vessels are significantly higher than those of smaller ships. Therefore, the use of this type of vessel is economically justified in conditions of significant draught (VBD, 2004).

The need to maintain adequate fairway depths also stems from the AGN Agreement (European Agreement on Main Inland Waterways of International Importance) signed in 1996. According to the agreement, free navigation on inland waterways of international importance should be ensured 365 days a year, except in regions where severe climatic conditions prevent effective icebreaking operations during the winter. Interruptions to the navigation period due to low water levels are prohibited. At all times, the permissible draught shall not be less than 1.2 m, and for at least 240 days a year the draught shall be maintained at the level recommended for the waterway in question (United Nations, 1997).

The observed weather anomalies are a factor disrupting the maintenance of the required waterway depths. It can be assumed that these problems even affect waterways considered to be the main axes of the European inland waterway system, such as the Rhine and Danube. The study therefore aims to demonstrate the relationship between weather conditions and the number of days on which guaranteed depths are not maintained. The hypothesis is that weather conditions are the cause of the upward trend in the number of days on which guaranteed depths are not maintained during the navigation period.

2. Ship Draft and Hydrological Conditions as Factors Limiting Inland Waterway Transport

The loading level of barges is a function of their draught. Even ships currently in use that are considered small, i.e. vessels with a load capacity of up to 1500 tonnes (such as the Johann Welker and Europaschiff types), have a draught of between 2.5 m and 2.70 m when fully loaded (Nakoinz, 2010; VBD, 2004). On the Rhine, GMS-110 motor barges with a full load (approx.

3000 tonnes) have a draught of 3.5 m, and pushed convoys (11,000 tonnes) have a draught of 4.0 m (Beuthe et al., 2013). This means that the navigable depth of the waterway must be correspondingly higher. The navigable depth is determined by the draught and a specified safety margin. For the Rhine waterway, the safety margin is set at a minimum of 32 cm (CCNR, 2024). For the Danube, the safety margin is assumed to be between 20 and 40 cm (Meinel, 2024). However, studies show that due to the increase in water resistance during movement, this margin should be at least 1.0 m, or even 1.5 m, for a draught of 2.5 m (Kulczk, Winter, 2003).

Extreme droughts that have hit Europe have limited the availability of cargo space on ships operating even on the Rhine. According to measurements taken at the Iffezheim lock in Germany, the average loading level of ships for dry cargo transport in 2022 ranged from 60.6% in February to 31.3% in August (CCNR, 2023c). Also in 2023, low water levels on the Rhine meant that ships had to operate at a loading rate of only 40-70%, depending on their size (Tagesschau, 2023). Shipowners agree to operate their fleets at lower load factors, as keeping many vessels 'in limbo' would entail too great a reduction in revenue in relation to fixed costs (CCNR, 2023a).

Similarly, on the Danube, the unfavourable hydrological situation in 2022, caused by exceptionally high temperatures and lack of rainfall, made navigation impossible, with the maximum draught of vessels at 2.5-2.7 m. On the Danube in July 2022, barges in pushed convoys were operated at an average load of 1,150 tonnes (upstream) and 1200 tonnes (downstream), while 110-metre-long motor barges were operating at loads ranging from 950 tonnes to 1100 tonnes. However, motor barges with a length of 135 m were not used for transport purposes due to insufficient transit depths (DC, 2023).

The limited depth of the waterway due to drought necessitates the construction of much lighter vessels with a shallower draught. An example of this type of solution is a gas tanker (110 m x 12.5 m) built in 2021 and operated by the shipping company HGK Shipping (Cologne). This ship can be used even at extremely low water levels (Podgórski, 2021). In 2023, the shipowner introduced two more modern chemical tankers, Courage and Curiosity (93 m x 10.5 m), which can be operated at a draught of 1.0 m while maintaining the appropriate manoeuvrability and stability requirements (HGK, 2023).

Ships designed for shallow waters have significantly lower efficiency compared to traditional vessels. It is therefore unlikely that this type of vessel will constitute a significant part of the overall transport capacity of this branch of transport. Research shows that the large-scale construction of shallow-draught vessels would only be justified if low water levels occurred during 60-80% of the navigation period (Van Dorsser, 2015).

Therefore, despite the observed low water levels, the general hypothesis of a trend towards a reduction in the size of inland waterway vessels is not confirmed. In 2023, the average deadweight tonnage in the tanker group was 2510 tonnes and in the dry cargo vessel group was 1447 tonnes. For comparison, in 2012, the average deadweight tonnage of these vessels was

1919 tonnes and 1296 tonnes, respectively. In the Rhine basin countries, no vessels with a deadweight tonnage of up to 1000 tonnes for the transport of liquid cargo have been built since 2020. There is a greater tendency to build new vessels with larger tonnage. The average deadweight of new tankers in 2023 was 4022 tonnes, compared to 2868 tonnes in 2022. In turn, the average tonnage of newly built dry cargo ships in 2023 was 2664 tonnes, compared to 2499 tonnes in 2022 (CCNR, 2024). The increase in the share of ships with greater draught in the overall fleet observed over the last few decades has therefore made water transport highly cost-effective (Vinke et al., 2022). The operation of large vessels allows the mass transport advantage of this mode of transport to be maintained, i.e. the ability to move a large quantity of cargo in a single transport cycle. With a high share of fixed costs in this mode of transport, the ability to move a larger cargo weight consequently means a reduction in unit transport costs. Fixed costs in this branch of transport account for 60 to 65% (Niedzielski et al., 2021; CCNR, 2023b).

Problems with maintaining the required depths mean an increase in unit transport costs and are also a factor disrupting the continuity and reliability of transport services (transport service reliability). As a result, the confidence of cargo managers and freight forwarders in inland waterway transport as a reliable supply chain partner is reduced and the risk of customers withdrawing from transport contracts increases. For example, in Belgium in 2023, the decline in demand for inland waterway transport led to more than 275 shipping companies filing for bankruptcy (Stefaniak, 2023).

Waterway depths are the result of investments and expenditure on maintenance. While investment expenditure covers expenditure on new projects and the modernisation of waterways, maintenance expenditure is largely related to dredging. It is therefore crucial for maintaining guaranteed navigable channel depths on existing waterways. However, these expenditures are not currently eligible for co-financing under the Connecting Europe Facility II (CEF II) programme. Therefore, these expenditures, both for waterways included in the core network and the comprehensive TEN, are currently covered by the budgets of individual countries (CCNR, 2024).

Another important determinant of existing depths is the volume of water flow in rivers, which is a result of precipitation levels. Lack of precipitation and accompanying droughts cause a reduction in average flow levels (Christodoulou, Christidis, Bisselink, 2020). In 2022, flows below the reference period average (1991-2020) were recorded in 63% of rivers. In contrast, 26% of rivers had exceptionally low flows and 20% had particularly low flows. The problem of record low flows in 2022 particularly affected rivers in the Danube, Rhine, Meuse and Loire basins (ESOTC, 2022). It can even be assumed that the frequency and scale of disruptions associated with low water levels will increase in the future (Scholten, Rothstein 2016; Van Dorsser, 2015).

Due to rapid climate change, greater problems can be expected in maintaining the required navigable depths, which may even result in the inability to transport cargo by inland waterways (De Jong, 2020). Maintaining adequate waterway depths is therefore essential for maintaining the efficiency of the inland waterway transport sector and increasing its role in the transport system.

3. Data and method

The actual depth of the fairway does not correspond to the water level readings at the water gauge station. Therefore, the following are used to determine the navigable depth of a waterway:

- for the Rhine waterway - an indicator referred to as the equivalent water level (WWL),
- for the Danube waterway - an indicator referred to as the low navigable water level (LNWL).

There is a relationship which shows that if the water level on the water gauge is consistent with the WWL or LNWL, the minimum guaranteed depth of the fairway for a given section is maintained (CNNR, 2024). Therefore, if on a given day the depth on the water gauge is lower than that specified for WWL (Rhine) and LNWL (Danube), this means that the guaranteed depth on the route is not maintained.

The number of days with a depth lower than the guaranteed depth was determined for 11 selected measuring stations on the Rhine waterway and 11 stations on the Danube waterway. The selection of measuring stations was based on data availability. Four measuring stations that are of key importance for navigation on these waterways were considered. On the Rhine, these stations are located in Kaub and Ruhrort, and on the Danube in Wildungsmauer and Hofkirchen (Christodoulou, Christidis, Bisselink, 2020).

The study used data from CCNR annual reports collected for the period 2015-2023. During data collection, a problem arose with incomplete data for measurements on the lower section of the Danube. The missing data concerned measurements at the Lom and Silistra water gauging stations (2015) and at the Calafat and Calarasi stations (2023). This problem was resolved by replacing the missing data with a specific numerical value. For this purpose, regression imputation was used (Piasecki, 2014; Pokropek, 2018). According to this method, it was assumed that there is a relationship between the water levels at the gauges for which the data gap problem occurred and the water levels at the neighbouring measuring station. The distribution of days on which depths lower than those guaranteed for the Rhine waterway were recorded is presented in Table 1, and for the Danube waterway in Table 2.

The study used analysis of variance of repeated measurements for Friedman ranks, i.e. Friedman repeated measures analysis of variance by ranks (Black, 2010). The method for repeated measurements was chosen because the data for the selected water gauges were recorded at repeated intervals (2015-2023). The use of a rank-based test is a result of the failure to meet the assumption of normal distribution of the variable in all compared periods. In the case of the Rhine, the Shapiro-Wilk test did not confirm the normality of the variable distribution in 2018, 2019 and 2022, and in the case of the Danube - in 2017. In the years mentioned, the test statistic (left-tailed test) was lower than the critical value W^*= 0.850 for $n = 11$ the significance level of $\propto = 0.05$. The conclusion was therefore based on the median value determined from the distribution of the number of days on which the guaranteed depths were not maintained on the Rhine and Danube waterways.

Table 1.
Number of days below the equivalent water level (EWL) for the Rhine gauge stations in years 2015-2023

Water gauge	2015	2016	2017	2018	2019	2020	2021	2022	2023
Basel (upper section)	8	7	24	48	0	0	0	7	4
Maxau (upper section)	30	27	28	80	0	0	6	23	8
Oestrich (middle section)	23	18	27	78	0	0	4	22	7
Kaub (upper section)	29	19	28	107	0	0	10	41	4
Cologne (lower section)	37	26	23	121	0	11	9	52	11
Duisburg-Ruhrort (lower section)	39	35	25	128	3	14	13	60	9
Emmerich (lower section)	46	36	25	134	4	25	27	65	9
Lobith (lower section)	34	29	25	131	4	20	16	64	11
Nijmegen (lower section)	31	29	24	136	3	17	14	62	10
Ijsselkop (lower section)	40	34	25	136	5	30	22	65	8
Tiel (lower section)	27	22	22	131	0	13	0	62	6

Source: CCNR, 2023a; 2024.

Table 2.
Number of days below the low navigable water level (NNWL) for the Danube gauge stations in years 2015-2023

Water gauge	2015	2016	2017	2018	2019	2020	2021	2022	2023
Pfelling (upper section)	106	22	38	148	47	84	36	71	79
Hofkirchen (upper section)	92	6	18	126	13	50	21	52	52
Kienstock (upper section)	35	12	24	55	7	5	27	6	21
Wildungsmauer (upper section)	54	23	37	89	27	31	47	36	30
Devin (upper section)	66	19	32	80	12	4	20	22	29
Budapest (middle section)	60	13	19	85	12	1	17	22	25
Bezdan (middle section)	66	19	16	97	31	0	38	71	36
Calafat (lower section)	118	36	92	114	100	53	53	127	82*
Calarasi (lower section)	75	24	32	82	89	23	47	119	57*
Lom (lower section)	62*	17	44	74	54	8	49	108	37
Silistra (lower section)	50*	18	22	77	75	25	53	44	43

* missing data estimated using regression imputation method.

Source: CCNR, 2023a; 2024.

When verifying the research hypotheses, they were transformed into a statistical hypothesis, giving it a formal (quantitative) structure (Black, 2010). In accordance with the most used concept of statistical hypothesis testing, the Neyman-Pearson approach was used, consisting in formulating null hypotheses and corresponding alternative hypotheses (Burnewicz, 2021). Two null hypotheses were formulated:

- the median number of days with a depth lower than the guaranteed depth does not change depending on weather conditions,
- the median distribution of days on which the waterway depth is lower than the guaranteed depth does not show an upward trend.

The alternative hypotheses are the opposite of the null hypotheses and were formulated as follows:

- the median number of days with reduced guaranteed depth changes in relation to the impact of weather conditions;
- the median number of days with reduced guaranteed depth shows an upward trend.

Among the proposed test statistics within the Friedman ANOVA method, the $T2$ *Iman-Davenport statistic* was used to examine the relationship between the weather factor and the number of days with reduced navigational depth in the compared periods. This statistic considers the correction for tied ranks and is therefore more recommended. To verify the null hypothesis of no increasing trend in the number of days on which depths were not maintained on the Rhine and Danube waterways, a *Page* test for trend was performed. The conclusions of this test were based on the statistic Z. The use of this statistic is reliable when the numbers n and $k$are sufficiently large ($k > 8$, regardless of the value of n) (Zaiontz, 2025). In this case, this condition is met, as $k = 9$, and $n = 11$.

As the base significant value was adopted the valueof $\propto = 0.05$. To tighten the evaluation criteria, the study was also conducted for a reduced level of $\propto = 0.001$, at which it is more difficult to reject the null hypotheses.

4. Results and discussion

The median values for the number of days on which depths lower than the guaranteed depth were recorded in 2015-2023 at selected water gauges on the Rhine and Danube waterways are shown in Fig. 2 and 3. The varying median values suggest that weather conditions influence the number of days with depths lower than guaranteed on these waterways.

As shown in Table 3, the test statistics $T2$ for the null hypothesis that the median number of days with depth below the guaranteed level does not vary depending on weather factors are 79.25 for the Rhine waterway and 15.25 for the Danube waterway. These statistics are significantly higher than the critical value determined from the F-Snedecor distribution table

for 8/80 degrees of freedom and $\propto = 0.05$ (2.06), and even higher than the critical value for $\propto = 0.001$ (3.70). Thus, even for a more stringent level of α, the null hypothesis must be rejected and the significance of the weather factor's impact on the number of days on which the guaranteed depths on the Rhine and Danube waterways were not maintained must be accepted.

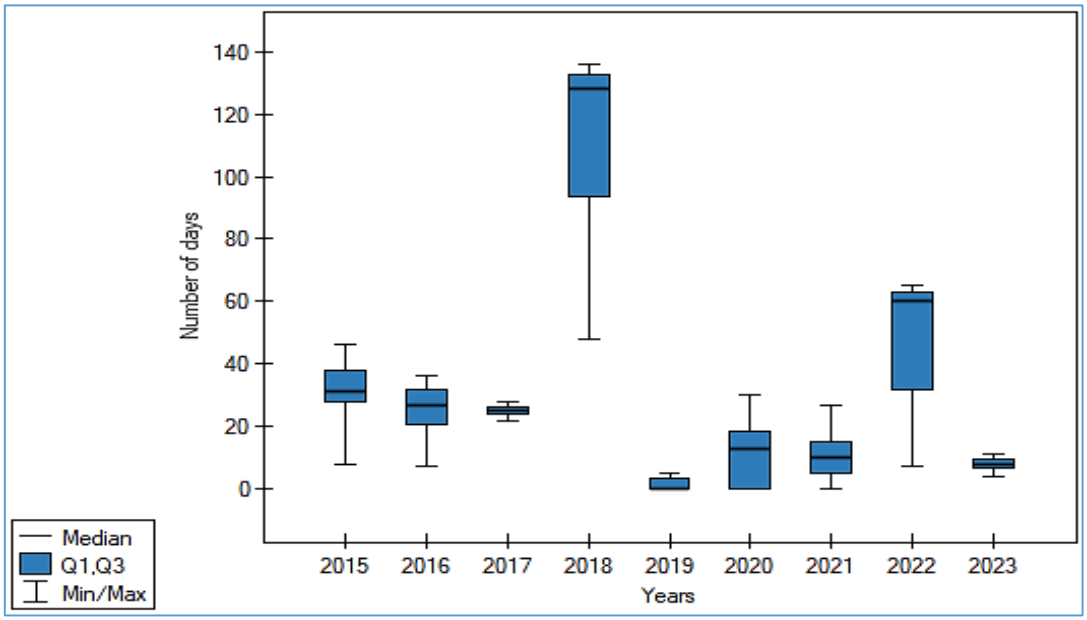


Figure 2. Median number of days with depth below the guaranteed level on the Rhine waterway in 2015-2023.

Source: own ellaboration using PQStat software.

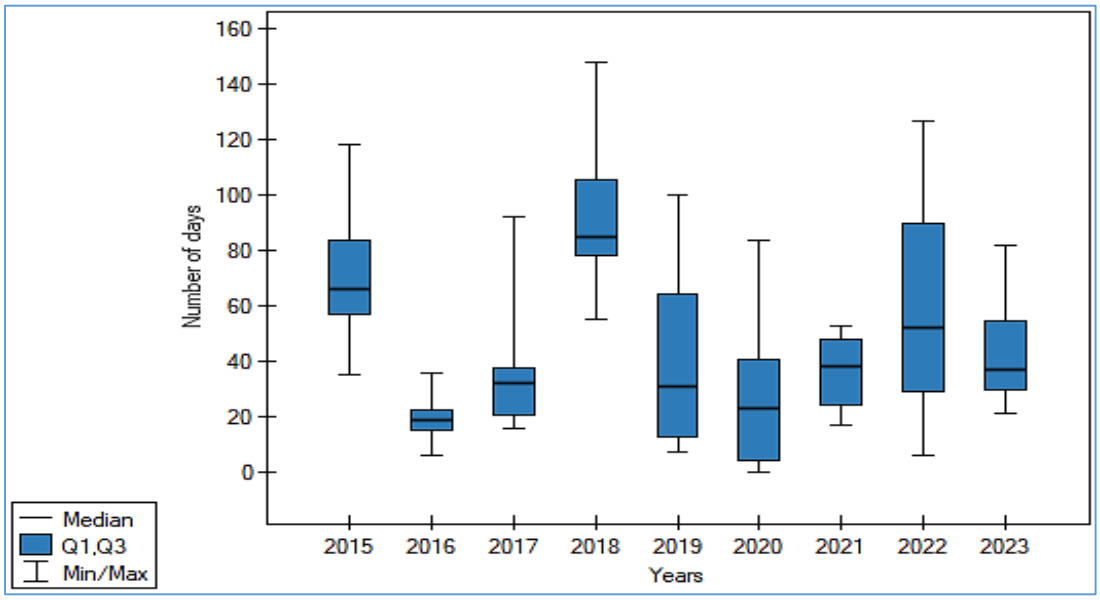


Figure 3. Median number of days with depth lower than guaranteed on the Danube waterway in in 2015-2023.

Source: own ellaboration using PQStat software.

Table 3.
Friedman ANOVA results

Specification	Rhine	Danube
Number of unspecified	0	0
Number of missing data	0	0
Significance level	0.05	0.05
*T*2 statistic Iman-Davenport	79.255583	15.963467
Degrees of freedom	8 / 80	8/80
p-value	<0.000001	<0.000001
Critical Values for T2 Statistic ($\propto = 0.05$)	2.06	

Source: own ellaboration using PQStat software.

In the case of the Rhine River, the study also confirms a statistically significant upward trend in the number of days with depths below the guaranteed depth. As shown in Table 4, the test statistic for the measurements taken on the Rhine waterway is 3.65. This value is even higher than the critical value for $\propto = 0.001$ (3.09). However, there is no basis for claiming that on the Danube, the number of days on which the depths on the shipping route fall below the guaranteed depth shows an upward trend. In this case, the test statistics are lower than the critical value.

Table 4.
Page test results for trend

Specification	Rhine	Danube
L statistic	2.218	2.454
Z statistic	3.652839	0.298481
One sided p-value	0.000259	0.382668
Critical Values for Z Statistic ($\propto = 0.05$)	1.65	
Critical Values for Z Statistic ($\propto = 0.001$)	3.09	

Source: own ellaboration using PQStat software.

The results obtained indicate that the problem of maintaining guaranteed depths is more pronounced on the Rhine than on the Danube. This is also confirmed by other studies on the impact of weather conditions on guaranteed depths at key points for maintaining navigation on these waterways. It is predicted that on the Rhine, both in the Ruhrort and Kaub measuring stations, the average number of days with low water levels will increase by the end of the century, with a slight increase in the Kaub area. In contrast, in areas critical for navigation on the Danube (Wildungsmauer and Hofkirchen), the number of days with low water levels is expected to decrease by the end of the century (Christodoulou, Christidis, Bisselink 2020).

Problems with maintaining the required guaranteed depths are directly related to the intensity of transport use of waterways. During the period under review, i.e. 2015-2023, traditional shipping (transport between Basel and the Dutch-German border) on the Rhine decreased from 185.7 million tonnes to 146.1 million tonnes. The volume of cargo transport on this main European inland waterway axis in 2023 was the lowest since the 1970s (CCNR, 2024). Between 2015 and 2023, a decline in transport was recorded on all sections of the Rhine waterway, with the largest declines in the middle (23.2%) and lower (22.3%) sections (BDB, 2025).

The Danube waterway is characterised by significantly lower transport intensity than the Rhine. On an annual basis, cargo transport on the entire navigable route from Kelheim (Germany) to the Black Sea via the Danube-Black Sea Canal and the Sulina Canal fluctuates between 34 and 40 million tonnes (CCNR, 2024). In recent years, a decline in transport on this waterway has been observed in the upper and middle sections. A different trend is observed in the lower section, especially in the Danube delta region. A significant increase in cargo transport in this region was recorded after 2022. Compared to 2020, freight transport on the lower section and in the Danube delta region increased by 4.8% in 2022 and by 41.8% in 2023 (Semyonovich Suvorov, 2024, p. 28). This is the result of the continuing good navigation conditions in this area and the increased use of this waterway for transport under the EU-Ukraine Solidarity Lanes system.

5. Summary, limitations and future research

The study provides compelling evidence that weather-related anomalies, particularly prolonged droughts, are a critical determinant of navigational depth on key European inland waterways such as the Rhine and Danube. The statistically significant increase in the number of days with insufficient depth on the Rhine confirms the growing vulnerability of inland waterway transport to climate variability. This directly affects the modal shift potential envisaged in EU transport policies and hampers the economic viability of larger, more efficient inland vessels.

The study was limited by gaps in hydrological data from several gauge stations, particularly on the lower Danube. While regression imputation was used to estimate missing values, this introduces potential biases and may not fully reflect complex local hydrodynamic conditions. Moreover, the analysis did not account for broader climatic indices (e.g. NAO, ENSO) or local interventions (e.g. dredging schedules), which could provide further explanatory power.

As for the future research the authors point out the following topics:

1. Climate Modelling Integration: Future studies should integrate regional climate model projections (RCMs) with hydrological and transport models to assess future navigability under various climate scenarios.
2. Cost-Benefit Analysis of Adaptation: A comprehensive economic assessment of adaptation strategies - such as riverbed stabilisation, dredging, and the design of low-draught vessels - is essential.
3. Fleet Modernisation Scenarios: Research should explore how expected changes in navigability affect fleet investment strategies and the technological transformation required for climate-resilient inland navigation.

4. Hydrological Forecasting and Risk Management: Advancements in real-time water level forecasting, especially under extreme climate events, would support better traffic planning and risk mitigation for freight operators.
5. Cross-modal Impact Assessment: The broader impacts on intermodal supply chains - especially modal shifts to rail or road in response to prolonged navigational limitations - should be quantified.
6. Institutional and Policy Frameworks: It is necessary to evaluate the effectiveness of current EU funding mechanisms and regulatory instruments in supporting the resilience and sustainability of inland waterways in the face of climate change.

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COMPARISON OF BUILDING SMOKE SIMULATION RESULTS: FDS, PATHFINDER VS. SPREADSHEETS

Marek DŁUGOSZ[1*], Angelika WÓJCIAK[2], Krzysztof KULCZYCKI[3], Paweł WOLNY[4]

[1] Independent, Łódź; marek.dlugosz98@gmail.com, ORCID: 0009-0002-0102-4613
[2] Lodz University of Technology, Lodz; biuro.awojciak@gmail.com, ORCID: 0009-0009-7753-5656
[3] Lodz University of Technology, Lodz; kulczyckikrzysztof8@gmail.com, ORCID: 0009-0000-3037-4781
[4] Lodz University of Technology, Lodz; pawel.wolny@p.lodz.pl, ORCID: 0000-0003-2161-4506
* Correspondence author

Purpose: The purpose of this study is to compare the results of smoke simulations in buildings obtained using the FDS (Fire Dynamics Simulator) program with those obtained using calculation sheets. The study aims to assess the effectiveness of different methods for smoke and evacuation analysis in the context of fire safety.
Design/methodology/approach: The study employed a comparison of smoke simulation results obtained from the FDS program and simple calculation sheets. Various evacuation scenarios and parameters, such as visibility through smoke and smoke temperature, were analyzed. Data from the literature were utilized, and simulations were conducted to evaluate the accuracy and effectiveness of each method.
Findings: The results showed that FDS offers more advanced and accurate simulations, while calculation sheets are faster and cheaper but have limited analytical capabilities. The simulations indicated that changes in the size of the simulation grid had little effect on visibility results, suggesting stability and reliability of the simulations.
Research limitations/implications: The limitations of the study include the need for appropriate skills to operate FDS and the constraints arising from simplifications in calculation sheets. Further research is suggested to better understand the dynamics of fire phenomena and to develop more advanced analytical tools.
Practical implications: The study has significant practical implications for fire safety engineers who can use the results to better plan evacuations and smoke management systems in buildings.
Social implications: The findings of the study may influence public policy regarding fire safety and social responsibility, contributing to improved quality of life by enhancing safety in buildings.
Originality/value: The article adds new value to the field of fire safety engineering by comparing different methods of smoke and evacuation analysis, which can be useful for engineers, architects, and institutions involved in building safety.
Keywords: safety engineering, software, fire safety.
Article category: model tests.

1. Introduction

Contemporary fire safety engineering increasingly relies on modern computational technologies due to growing requirements for ensuring an adequate level of fire protection. This, in turn, has contributed to the intensive development of tools for predicting fire development and assessing the effectiveness of the protective measures used.

The choice of the appropriate method of smoke analysis and evacuation depends on the type of facility, the technical capabilities available, and how accurately we want to assess the fire risk. For simple buildings, where there are no crowds of people or complex structures, it is often sufficient to use simple spreadsheets—they are quick and inexpensive. However, it should be remembered that their accuracy in reproducing real physical phenomena is limited.

For more complex buildings with a high degree of architectural complexity, a large number of users, and special requirements for evacuation and smoke extraction, it is recommended to use advanced simulation tools such as FDS and Pathfinder. They allow for a more accurate analysis of hazards, evacuation planning, and the adaptation of technical solutions to specific needs. However, it is important to ensure that the results are interpreted correctly and that the people operating these programs are properly trained.

Today, when designing modern and safe buildings, it is important to skillfully combine simple methods with computer simulations in order to achieve the best results without unnecessary costs.

2. Characteristics of methods for smoke analysis and evacuation

2.1. FDS (Fire Dynamics Simulator)

Fire Dynamics Simulator (FDS) is a computer model that simulates fire-driven fluid flow. It is a computational fluid dynamics (CFD) model that numerically solves the Navier-Stokes equations for low-velocity flows, with an emphasis on smoke and heat transport from fires. Together with the Smokeview program, they form a single package. It is open-source software, which makes it a free tool. The creators of this software are the National Institute of Standards and Technology (NIST) of the United States Department of Commerce (McGrattan et al., 2007). FDS is based on entering object parameters in a text file and through the CMD command line (for DOS-based systems), the program performs flow simulations.

Smokeview is a separate visualization program that is used to display the results of FDS simulations. It allows the results to be animated on a computer screen and has a simple menu-based interface.

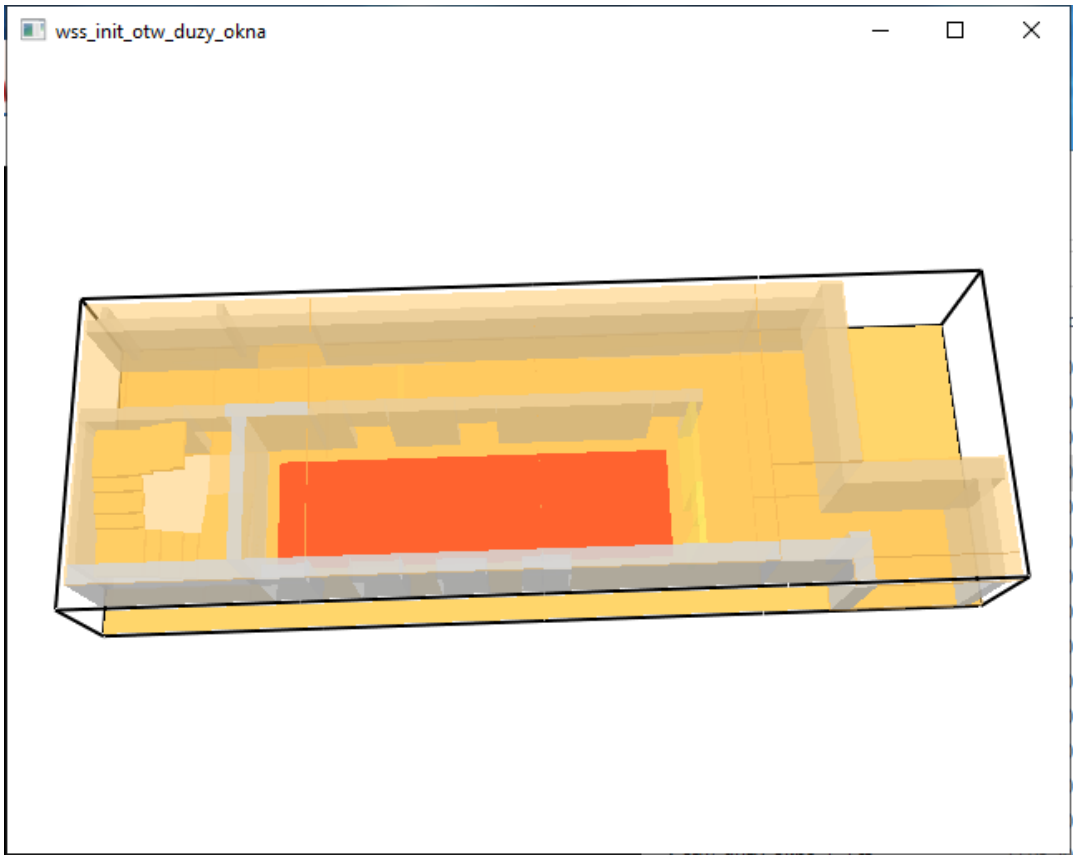


Figure 1. Smokeview window.

FDS is used to design smoke management systems, study sprinkler and detector activation, and reconstruct fires in residential and industrial environments. It is a tool for solving practical fire protection problems and for studying the basic phenomena associated with fire dynamics and combustion.

FDS and Smokeview can be used in practice to simulate and analyze fire scenarios, which is useful in the design of fire protection systems and in research on fire dynamics. Users can create input files for FDS, run simulations, and analyze the results using Smokeview, which allows for a better understanding of the behavior of fire and smoke under various conditions.

2.2. Pathfinder

Pathfinder is a program developed by Stigo that is used to simulate the evacuation of people from buildings. It works on the basis of an agent model – each person in the simulation is a separate agent who reacts to the environment and other people (Thunderhead Engineering, 2023). This allows you to analyze various evacuation scenarios, e.g., during a fire, panic, or poor visibility. The program also allows you to load building plans from CAD, PyroSim, and other files.

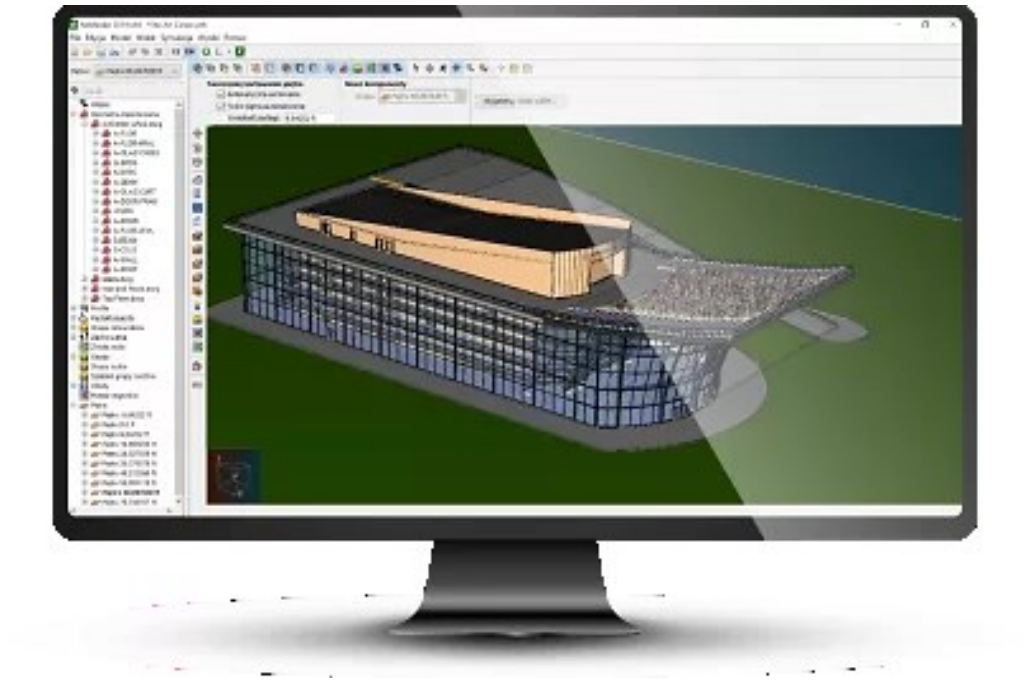


Figure 2. Pathfinder program image.

Source: https://pyrosim.pl/program-pathfinder/

The Pathfinder program, combined with high-quality animated 3D results, allows you to quickly obtain reliable answers using the software's artificial intelligence.

Such simulations are particularly valuable where it is impossible or dangerous to conduct a real experiment, and they also allow mathematical and physical models to be used in a way that produces reliable and accurate results.

What you can do with this tool:

- Independently plan various evacuation scenarios.
- Work on a drawing or building plan loaded from a graphic file (e.g., jpg).
- Record videos showing the evacuation process and save them in video format.
- Automatically recognize evacuation routes based on CAD drawings.
- Ability to independently define elements of the environment, such as rooms, doors, stairs, or slopes.
- Great freedom in creating different profiles of people participating in the simulation (e.g., age, mobility).
- Support for CAD files (dwg, dxf) and models from PyroSim (psm, fds), also in 3D.
- Creation of graphs showing how many people move through specific zones.

Advantages:

- attractive 3D visualization,
- intuitive interface,
- ability to test multiple evacuation scenarios,
- taking individual characteristics into account (age, fitness).

Disadvantages:

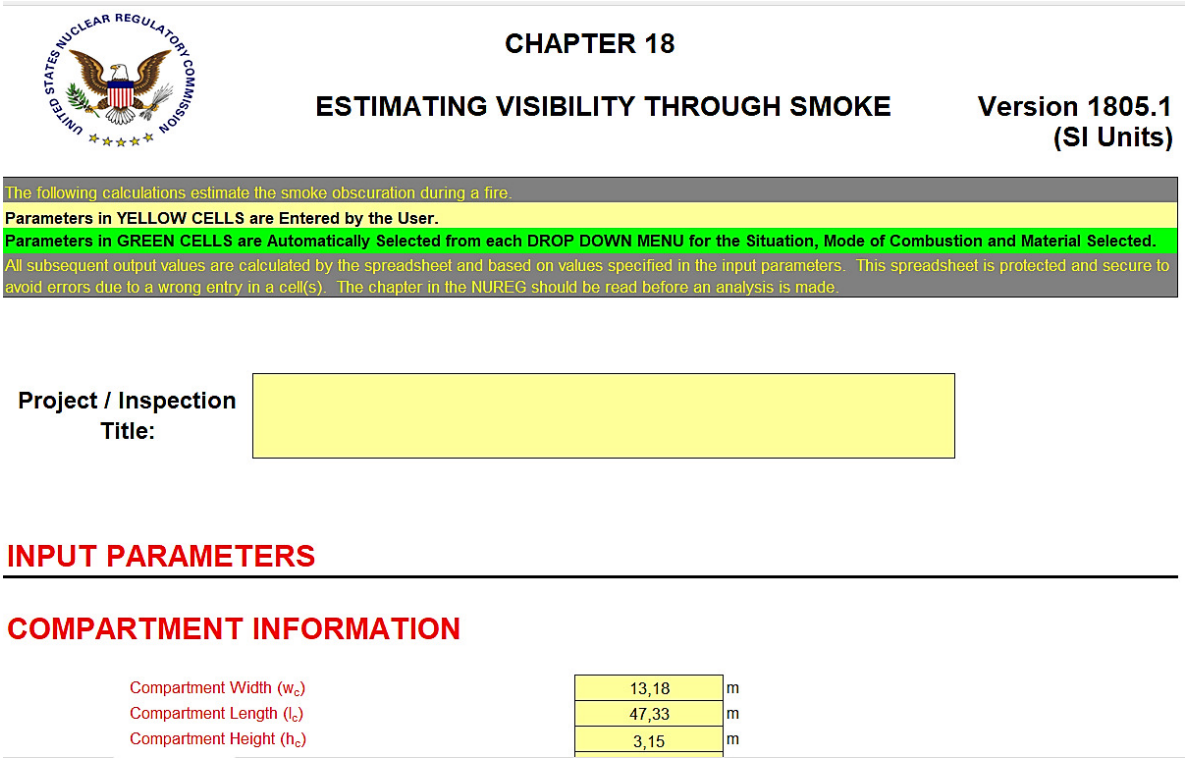
- no direct modeling of fire phenomena,
- license cost (from approx. USD 4500) (Prauzner, 2014),
- limited compatibility with certain European standards.

Despite its numerous advantages, the program's limitations—including the inability to model fire phenomena, high license cost, and partial incompatibility with European standards—indicate the need for careful evaluation of its applications in specific projects. Nevertheless, for entities seeking effective solutions for simulating movement in emergency conditions, investing in Pathfinder may prove justified, especially due to the possibility of testing complex evacuation scenarios taking into account individual factors. Despite certain shortcomings, this tool sets the standard in the field of digital safety analysis, integrating simulation precision with intuitive operation.

2.3. Spreadsheets

Simulation of smoke in buildings using spreadsheets Excel spreadsheets are used in the assessment of evacuation conditions because they are simple and inexpensive. The well-known program from Microsoft's Office 365 suite, a popular office software package, is used for this purpose. To make good use of this tool, you need to be familiar with formulas, such as those used for calculations and formulas used by Excel. Everything is made as accessible as possible for anyone who does not use professional engineering software on a daily basis.

The calculation methods, e.g., in spreadsheets, are based on formulas from standards such as PN-B-02852:2001 or PN-EN 12101-5. To use them, you need to know the parameters of the building, the expected fire conditions, and the rules for selecting smoke extraction equipment. It all depends on which mathematical formulas we use. In this study, we will use a spreadsheet based on the book "Principles of Smoke Management" (Klote, Milke, 2002).



CHAPTER 18

ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.1
(SI Units)

The following calculations estimate the smoke obscuration during a fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from each DROP DOWN MENU for the Situation, Mode of Combustion and Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s). The chapter in the NUREG should be read before an analysis is made.

Project / Inspection Title:

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	13,18	m
Compartment Length (l_c)	47,33	m
Compartment Height (h_c)	3,15	m

Figure 3. Estimating visibility through smoke – Excel spreadsheet.

2.3.1. How does it work in Excel?

In Excel, you can easily program relationships that show how quickly smoke builds up in a given room. All you need to do is create a table in which you enter input data such as room volume, smoke generation rate, and acceptable concentration, and then apply the appropriate mathematical formulas that use these values to calculate the time it will take for the smoke to reach a dangerous concentration. Thanks to the spreadsheet functions, we can also estimate how low the smoke layer will fall over time and how long a safe evacuation space will be maintained. A spreadsheet prepared in this way allows you to quickly analyze different scenarios by changing only a few numbers in the table. This is a great solution at the preliminary analysis stage, when we do not yet have access to specialized programs. The fire power, as a key input parameter for any simulation, can also be estimated based on available data and formulas described in the technical literature Pyrosim.pl. (2021). Fire power as the most important input parameter for CFD simulations (Fliszkiewicz et al., 2012).

Potential errors and limitations:

- Ignoring the variability of thermal and pressure conditions.
- Lack of representation of dynamic phenomena (e.g., changes in smoke volume, turbulence).
- Assumption of a constant smoke flow regardless of the fire development phase.
- No information about the smoke layer and its impact on visibility.
- Limited possibilities for validating results without a real model.

Advantages:

- simplicity and speed of calculations,
- low costs,
- acceptance by building control authorities,
- data can be quickly changed and different scenarios can be checked,
- almost every student or employee has Excel.

Disadvantages:

- significant simplifications of the model,
- Excel will not show how smoke moves,
- lack of dynamics of phenomena,
- inadequate for unusual objects (STIGO, 2025).

2.3.2. How much does it cost?

Although using Excel for such simulations does not require significant financial outlay, it is worth mentioning a few things. Many universities provide students with free access to this program under an educational license, which makes it a particularly attractive tool for learning and analysis. However, if you do not have such access, the cost of purchasing an annual license is approximately PLN 200-500, or a monthly subscription as part of Microsoft 365. Added to this is the time you need to spend learning how to use it – although most users know the basics of Excel, creating a working simulation spreadsheet requires some practice. There are also paid courses that teach more advanced use of Excel – their prices start at around PLN 500. Nevertheless, compared to specialized engineering programs, Excel remains a much cheaper and easier-to-use solution.

3. Results

For our study, we will use the two programs mentioned above: FDS and MS Excel. The parameter we will compare is visibility through smoke. We will use the data used in the article Simulation of Heat and Smoke Behavior for Wood and Subway Fires by Fire Dynamics Simulator (FDS) (Sonh et al., 2010).

3.1. FDS

The research conducted by the Koreans focused on analyzing the behavior of smoke and heat in wood and subway fires using the FDS simulator. In terms of visibility through smoke, the study found that changes in the size of the simulation grid had little effect on visibility results, meaning that the simulations were stable and reliable at smaller grid sizes.

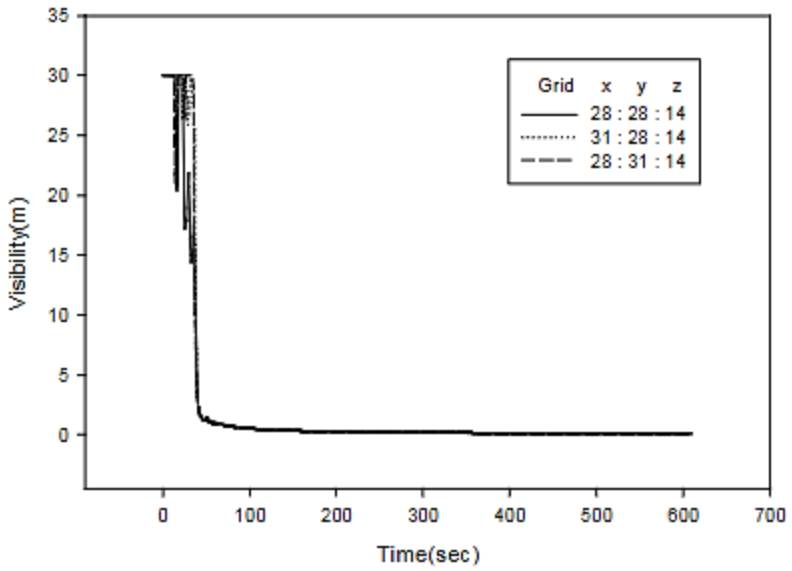


Figure 4. Changes in visibility depending on grid size at a height of 1.5 m and a distance of 7.5 m in a subway fire.

Source: (Sonh et al., 2010).

In addition, other parameters such as smoke temperature and CO concentration were observed in the study. The simulation results showed that the smoke temperature at a height of 2 meters initially rose rapidly, then gradually increased, and after about 500 seconds began to drop rapidly due to the smoke settling and dispersing. The CO concentration was slightly higher for larger grid sizes at certain points, but overall the values were similar for different configurations.

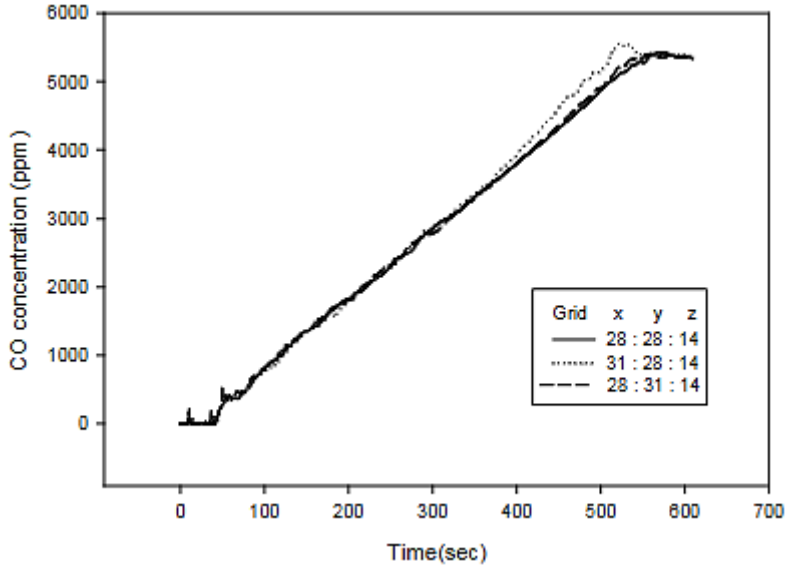


Figure 5. Changes in maximum CO concentrations depending on mesh size at a height of 1.5 m and a distance of 7.5 m during a subway fire.

Source: (Sonh et al., 2010).

3.2. Excel

For comparison, an Excel spreadsheet based on the book "Principles of Smoke Management" (Klote, Milke, 2002) will be used. The data was entered based on the Korean article and is shown in the table below.

Table 1.
Input data

Parameter	Value	Unit
Compartment Width (w_c)	3.0	m
Compartment Length (l_c)	20.00	m
Compartment Height (h_c)	2.75	m
Mass of Fuel Burn (M_f)	2.77	kg

$$S = \frac{K}{\alpha_m \times m_p} \tag{1}$$

where:
S – visibility through smoke (m),
K – proportionality constant,
α_m – secific extinction coefficient (m^2/kg),
m_p – mass concentration of particulate (kg/m^3).

Compartment Volume Calculation

$$V = w_c \times l_c \times h_c \tag{2}$$

where:
V – volume of the compartment (m^3),
w_c – compartment width (m),
l_c – compartment length (m),
h_c – compartment height (m).

Mass of Particulates Produced (airborne particulate)

$$M_p = y_p \times M_f \tag{3}$$

where:
M_p – mass of particulates produced (kg),
y_p – particulates yield,
M_f – mass of fuel consumed (kg).

Mass Concentration of the Particulates Calculation

$$m_p = \frac{M_p}{V} \tag{4}$$

where:
m_p – mass concentration of the particulates (kg/m^3),
M_p – mass of particulates produced (kg),
V – volume of the compartment (m^3).

Summary of Results

Visibility Through Smoke Calculation

$$S = \frac{K}{\alpha_m \times m_p} \tag{5}$$

Answer S = 2.77 m = 9.08 ft

Table 2.
Summary of results from Excel spreadsheet

Parameter	Value	Unit
Compartment Width (w_c)	3.0	m
Compartment Length (l_c)	20.00	m
Compartment Height (h_c)	2.75	m
Mass of Fuel Burn (M_f)	2.77	kg
Volume of the compartment (V)	165.00	m^3
Mass of particulates produced (Mp)	0.04	kg
Mass concentration of the particulates (mp)	2.52 x 10^{-4}	kg/m^3
Visibility through smoke (S)	2.77	m

Visibility through smoke according to the Excel sheet is 2.77 m.

4. Summary

There is no doubt that Fire Dynamics Simulator (FDS) is a more advanced fire simulation tool than a simple spreadsheet. The simulation uses the Navier-Stokes equation for low-velocity flows, which allows for more accurate prediction of fire behavior. On the other hand, the Excel spreadsheet allows for quick and inexpensive preliminary smoke analysis and enables easy testing of different scenarios by changing the input data.

In terms of accessibility, FDS is a free program, but the threshold for using it is quite high and requires at least an average knowledge of DOS-based commands (for Windows) and programming language, as FDS does not have a graphical user interface (GUI) and data for this program is entered in text files.

When it comes to Excel, its advantage is undoubtedly its simplicity of use and the vast possibilities it offers in selecting mathematical components. Although formulas can be somewhat difficult, the program offers extensive support during spreadsheet editing. The disadvantage of this solution is, of course, the author's knowledge. While FDS is a ready-made product that we know or can predict how it will behave, with a spreadsheet we are the

programmers ourselves and we need to know what parameters and formulas to use. If we rely on ready-made solutions, we don't have to worry about this problem. Another issue is that the spreadsheet will give us one or several results from a given point on the timeline. It will not simulate how the object will behave throughout the entire simulation.

In the practice of fire safety engineering, the complementary use of tools such as Excel and FDS can bring significant benefits. Excel can be used to quickly test different scenarios and parameters, allowing for a preliminary understanding of smoke dynamics and evacuation. This allows engineers to quickly identify potential problems and focus on key aspects that require more detailed analysis. Here, for example, they will use FDS, which will be used for final validation or more detailed analysis of smoke physics in more advanced building structures.

In summary, FDS offers more advanced and accurate simulations, but is more complex and time-consuming to use. Excel, on the other hand, is simpler and faster, but its capabilities are limited to basic analyses and it does not reflect the dynamics of fire phenomena.

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PERSPECTIVES ON USING INNOVATIVE DIGITAL TECHNOLOGIES IN ARCHITECTURE FOR FORENSIC HANDWRITTEN INK ANALYSIS

Klaudiusz FROSS[1*], Adam BUCZEK[2], Krzysztof GROŃ[3], Tomasz SZULIŃSKI[4], Roxana FROSS[5]

[1] Silesian University of Technology, Faculty of Architecture; klaudiusz.fross@polsl.pl, ORCID: 0000-0002-0013-7619
[2] Upper Silesian Academy, Department of Law and Administration, Katowice; a.buczek@op.pl, ORCID: 0000-0003-1395-7541
[3] Silesian University of Technology, Faculty of Architecture; krzysztof.gron@polsl.pl, ORCID: 0000-0002-5152-0167
[4] Silesian University of Technology, Faculty of Architecture; tomasz.szulinski@polsl.pl, ORCID: 0000-0001-6005-3786
[5] Silesian University of Technology, Faculty of Architecture; frossroxana@gmail.com, ORCID: 0000-0003-2783-5086
* Correspondence author

Purpose: The paper aims to explore the application of modern 3D digital imaging tools, originally developed for architectural design, in forensic handwriting analysis and technical document examination. It seeks to provide objective, quantitative methods for assessing ink layer thickness in handwritten signatures, a parameter reflecting individual writing pressure and psychomotor characteristics.
Design/methodology/approach: An interdisciplinary research team, comprising experts in law, forensic science, architecture, software, digital technologies, and design, conducted the study. The approach combined 3D digital imaging techniques, image processing algorithms, and quantitative analysis to measure ink layer thickness in handwriting samples. The theoretical scope integrates architectural digital modeling methodologies with forensic document examination.
Findings: The study demonstrates that algorithms derived from 3D architectural imaging allow precise, quantitative measurement of ink layer thickness. This method provides reliable, reproducible data for assessing individual writing pressure, reducing subjectivity in traditional forensic handwriting evaluation. The approach also enables population-level analysis of writing characteristics.
Research limitations/implications: The research is limited to the types of handwriting samples and ink used in the study. Future studies could expand to different pen types, substrates, and larger population datasets. The methodology suggests potential for integration with automated forensic handwriting systems.
Practical implications: The developed techniques offer forensic experts' objective, reproducible tools for evaluating ink layer thickness, improving the accuracy and reliability of handwriting analysis in legal proceedings. The approach could inform the development of software solutions for document examination and digital evidence processing.

Social implications: By improving the accuracy of forensic handwriting analysis, the research contributes to the integrity of legal proceedings and public trust in forensic evidence. Enhanced reliability in document examination could influence law enforcement practices, judicial outcomes, and public confidence in the justice system.
Originality/value: The paper introduces a novel interdisciplinary approach by applying architectural 3D imaging techniques to forensic handwriting analysis. It provides new methodologies for objective, quantitative evaluation of ink layer thickness, valuable to forensic scientists, law enforcement, and researchers in digital forensics and document examination.
Keywords: forensic science, digital forensics, architecture, 3D imaging tools, handwriting analysis.
Category of the paper: Research paper.

1. Introduction to research

In recent decades, modern digital methods for architectural design have developed rapidly, extending into the virtual realm. Virtual environments can be created using platforms such as Unreal Engine. Software including Autodesk 3ds Max, Foundry Modo, Substance Designer, Rhino, Adobe Photoshop, and Adobe Fuse support modelling, texturing, lightmapping, and UV mapping, among other tasks. Animation can be produced using programs such as Premiere Pro or Mixamo. The combination of Rhino and Grasshopper enables the creation of parametric scripts and spaces. Virtual reality (VR) can be experienced through devices such as Meta Quest, Oculus, HTC Vive, Google Daydream, Samsung VR headsets, touchscreens, and mobile applications on iPads or iPhones, and is increasingly integrated into design workflows. VR-enhanced projects may include apartment sales presentations for developers or furniture design proposals. Mixed reality devices, such as Microsoft HoloLens 2, allow for presenting building models and inspecting structures during construction.

3D scanners, often paired with drones or smartphone apps, are increasingly used to inventory rooms, objects, or entire areas. Applications include grayscale numerical analysis, computational design, and parametric modelling based on CAD software, as well as algorithmic design. Widely used software for generating and processing 3D models includes Quad Remesher, Reality Capture, Moi3D, Fusion360, 3DCoat, Adobe CC, and Houdini. Graphical algorithm editors are particularly important; for example, the Grasshopper editor integrated with Rhinoceros 8 allows users to create form-generation algorithms without coding, generate geometry with custom attributes, and arrange hatches and annotations efficiently.

These technologies enable the creation of highly precise, photorealistic 3D models, which have applications beyond architecture, including industrial design, mechanics, geology, archaeology, and medicine. 3D digital imaging methods are increasingly employed in a wide range of expert practices within law enforcement and the justice system, covering areas such as biomechanics, molecular biology, toxicology, thanatology, forensic traumatology, ballistics, trace analysis, and accident reconstruction.

2. Methodology, purpose and scope of research

The research presented here is innovative, pioneering, and groundbreaking, representing some of the first effective attempts to apply modern 3D digital imaging tools from architecture to the forensic analysis of handwritten signatures (Fross, Buczek, Groń, 2024). This study focuses specifically on analyzing digital images of ink layer thickness in handwritten notes using grayscale numerical analysis. Determining ink layers is a critical component of forensic technical document examination and encompasses issues such as the analysis of inks, ballpoint pens, gels, stamps, seals, computer printouts, and xerographic copies.

In expert practice particularly in the context of forgery detection questions often arise regarding whether specific records (e.g., individual components of a will) were written using one or multiple ink layers, the chemical composition of these layers, whether the records were created simultaneously, and the sequence of recording. Although pilot in nature, the research described in this article offers a valuable supplement and a fresh perspective on standard methods used in forensic science.

Traditional forensic approaches to ink analysis include specialized workstations such as the Foster+Freeman QDE VSC8000/HS, which combines advanced digital imaging, multi-wavelength illumination, and a built-in microspectrophotometer. Spectroscopic methods, including Raman and infrared spectroscopy, as well as chemical approaches such as thin-layer chromatography and high-performance liquid chromatography, are widely employed. Additional research explores advanced techniques such as time-of-flight secondary ion mass spectrometry (ToF-SIMS), laser micro-sampling coupled with inductively coupled plasma mass spectrometry (LA-ICP-MS), and capillary electrophoresis (CE), among others.

The present research focuses on a single parameter the ink layer thickness which can be used to infer individualized writing pressure. Other properties, including the color of the ink coating and the indentations or reliefs created in the ink layer, are investigated in separate studies using different methodologies.

2.1. A concise description of the research methodology

The experimental method involved the use of Rhino 7.34.23267.11001 in combination with Grasshopper 1.0.0007 for all computational analyses. The research was conducted in two stages. In Stage 1, a single signature was analyzed, and an algorithm was developed to numerically characterize the degree of saturation of its ink lines. The outline of the signature was visualized, incorporating numerical values representing the saturation and thickness of the ink lines in the base signature. In Stage 2, the initial algorithm was expanded into a script that enabled comparative analysis of ink thickness distribution, represented on a grayscale, across multiple graphic structures. In this stage, four signatures by one of the co-authors, created with four different ink layers, were analyzed, and the results were visualized. A detailed description of the research procedure is provided in Section 4.

2.2. Theoretical background and foundations of research

Extensive literature exists on the forensic examination of documents, including studies addressing the application of concealing agents. The most important authors in the world include: Joy T. Kunjappu (Joy, 2003), Raj Kumar, Wiszal Sharma (Raj, Sharma, 2017), Yao Wu, Chun-Xi Zhou, Jing Yu, Hai-Ling Liu, Meng-Xia Xie (Wu, Zhou, Yu, Liu, Xie, 2012), Agnieszka Koenig, Celine Weyermann (Koenig, Weyermann, 2018), André Braz, Maria López-López, Carmen García-Ruiz (Braz, López-López, García-Ruiz, 2013), Jay Siegel, John Allison, Donna Mohr, Jamie Dunn (Siegel, Allison, Mohr, Dunn, 2005), Georgina Sauzier (Sauzier, 2023), Anastasia V. Kravchenko, Daria V. Makeeva, Ilja Tumkin, Andrei V. Kalinichev (Krawczenko, Makeeva, Tumkin, Kaliniczew, 2024), Nikolai Ju. Tyuftyakov, Andrei V. Kalinichev, Nadezhda V. Pokhvishcheva, Maria A. Peshkova (Tiuftiakow, Kaliniczew, Pochwiszczewa, Peszkowa, 2021), Matías Calcerrada, Carmen Garcia-Ruiz (Calcerrada, Garcia-Ruiz, 2015), L. Ortiz-Herrero, M. I. Maguregui, L. Bartolomé (Ortiz-Herrero, Maguregui, Bartolomé, L. 2021). In Poland, the following authors publish, among others: Klaudiusz Fross, Adam Buczek, Krzysztof Groń (Buczek, 2006; Buczek, Groń, 2015; Fross, Buczek, Groń, 2024), Andrzej Łuszczuk, Krystian Łuszczuk, Mieczysław Goc, Tadeusz Tomaszewski (Goc, Łuszczuk, Łuszczuk, Tomaszewski, 2012; Łuszczuk, Goc, Łuszczuk, 2014, 2015), Roman Ptak, Bartosz Żygadło (Ptak, 2006, 2012; Ptak, Żygadło, 2014), Jacek Reiner, Mariusz Mrzygłód, Grzegorz Rusek, Mirosław Owoc, Rafał Cieśla, Michał Januszkiewicz (Reiner, Mrzygłód, Rusek, 2014; Rusek, Cieśla, Ptak, Januszkiewicz, 2019; Rusek, Reiner, Ptak, Owoc, Mrzygłód, Cieśla, 2012), Jacek Jarnicki (Jarnicki, 2012).

For modern equipment used in handwriting identification examinations, including issues such as determining the chronology of entries (relative age) and absolute age analysis, see, for example, E. Gruza, M. Goc, and J. Moszczyński, Kryminalistyka. *Czyli o współczesnych metodach dowodzenia przestępstw*, Wolters Kluwer, Warsaw 2020, pp. 462-471. In the context of examining concealing agents, forensic science employs numerous methods described in Analityka sądowa (Kościelniak, Król, Wietecha-Posłuszny, Woźniakiewicz, 2023).

Similarly, modern digital methods developed for architectural design have been widely described, including software for 3D visualization, 3D scanning, 3D printing, virtual reality (VR) (Urbanowicz, Szuliński, 2020, 2021) and mixed reality (MR) (Fross, Fross, Szuliński, 2022). It is important to emphasize the rapid development and significant variability of architectural software in recent years, evolving from early CAD programs such as AutoCAD and ArCADia, through complex 3D visualization programs like 3ds Max, then to more user-friendly solutions such as ArCon and ArchiCAD, and currently widely used programs including Revit, SketchUp, and Blender (Szuliński, 2022). Achieving high-quality 3D visualizations often requires the use of multiple programs, culminating with graphics software such as Photoshop. The market drives the demand for creating 3D drawings, visualizations, and models,

with current trends emphasizing project digitization and design integrated with BIM software (Fross, Fross, Szuliński, 2022).

In forensic science, the transition from conventional to digital 3D imaging methods has created disproportionately greater opportunities for inference and assessment. Modern 3D laboratories offer extensive technical and technological capabilities for mapping and analysing the complex biology of the human body and its surrounding environment within a virtual three-dimensional space. Key technologies employed include 3D laser scanning, photogrammetry, modelling, texturing, and 3D animation (Maksymowicz, Tunikowski, 2018).

The primary objective of forensic handwriting and document analysis is the identification of the writer. The scope of such research encompasses comprehensive examinations of wills, continuous texts, signatures, anonymous letters, and phenomena collectively referred to as 'handwriting pathology.' This includes the handwriting of individuals affected by various conditions, such as mental illness, Parkinson's disease, Alzheimer's disease, aging (particularly in the context of drafting wills), and other relevant factors.

2.3. Description of the research and methods

Items Using Rhino 7.34.23267.11001 and Grasshopper 1.0.0007, we first developed an algorithm to quantitatively assess the degree of saturation of the writing lines with the covering material (Fig. 1).

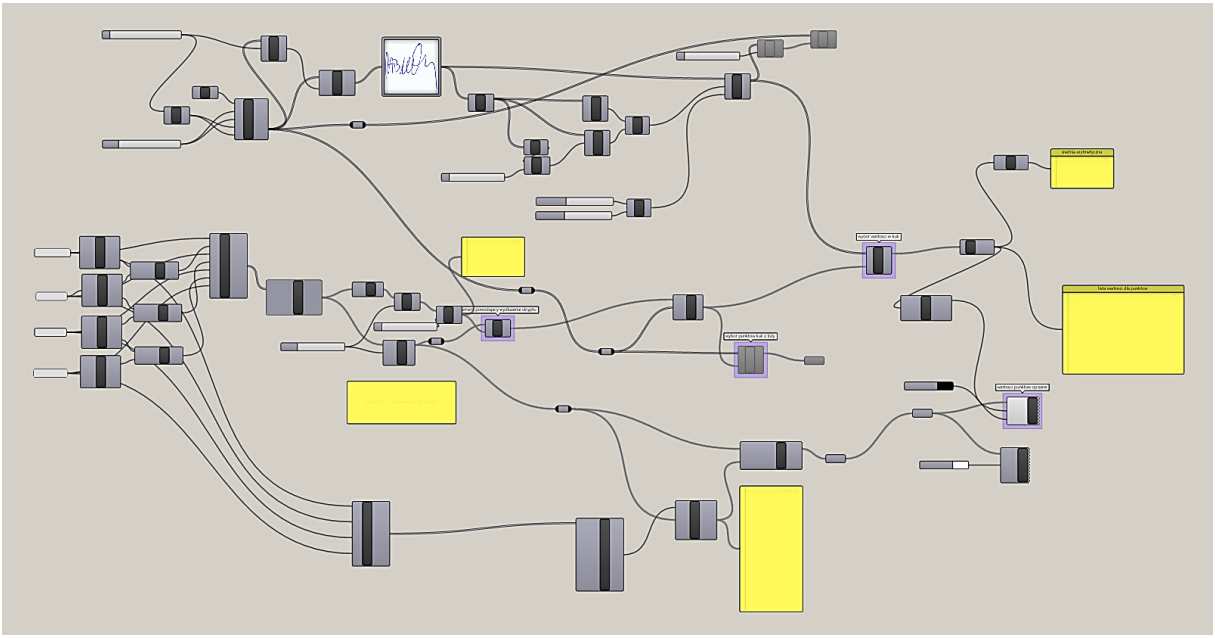


Figure 1. Algorithm providing a numerical characteristic of the digital image of the degree of saturation of the writing lines with the ink.

At the current stage of research, the algorithm remains semi-automatic and has been tested primarily on short graphic structures, including signatures and initials[1]. After scanning the analysed structure, the procedure began by manually tracing a line through the centre of the writing, across the entire surface of the signature, to define the pixel analysis area. In the present case, the algorithm was configured to divide this defined outline into 300 sets. It then sampled pixels along the traced line and calculated arithmetic means for each set, corresponding to the degree of line saturation (see Figures 1 and 2).

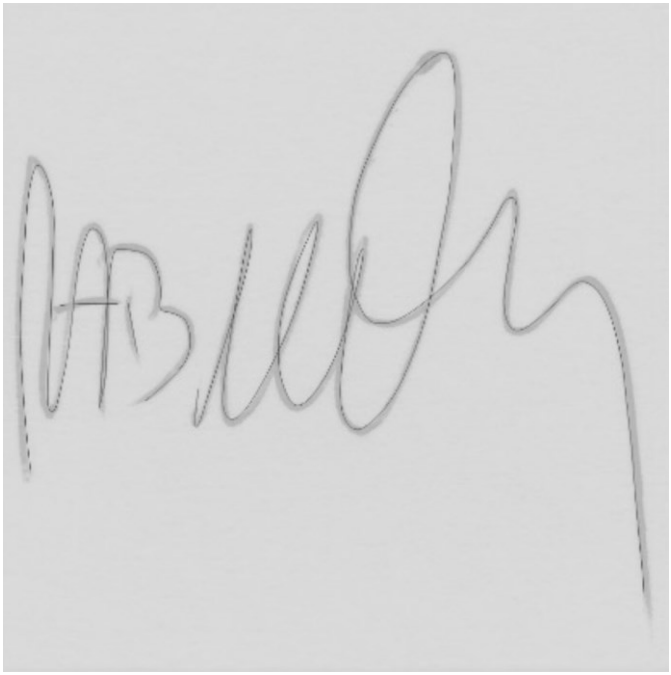


Figure 1. Manually drawn line/outline of the base signature scan.

Figure 3 defines a 1-100 grayscale based on scan brightness. This scale enables the quantification of the signature's pressure sensitivity, representing the shade (value) of the line across its 300 divided sections.

A precise, numerical characterization of handwriting line thickness was obtained, allowing the identification of extreme values from the minimum to the maximum and the calculation of the average value. This approach facilitates the quantitative determination of a highly personalized, and therefore diagnostically significant, handwriting parameter that can support individual identification. Figures 4 and 5 illustrate a visualization and a 3D model of the procedure as applied to the page containing the analyzed signature.

[1] The graphic structure (visible in Fig. 1) described later in the text is the signature of one of the co-authors of this publication.

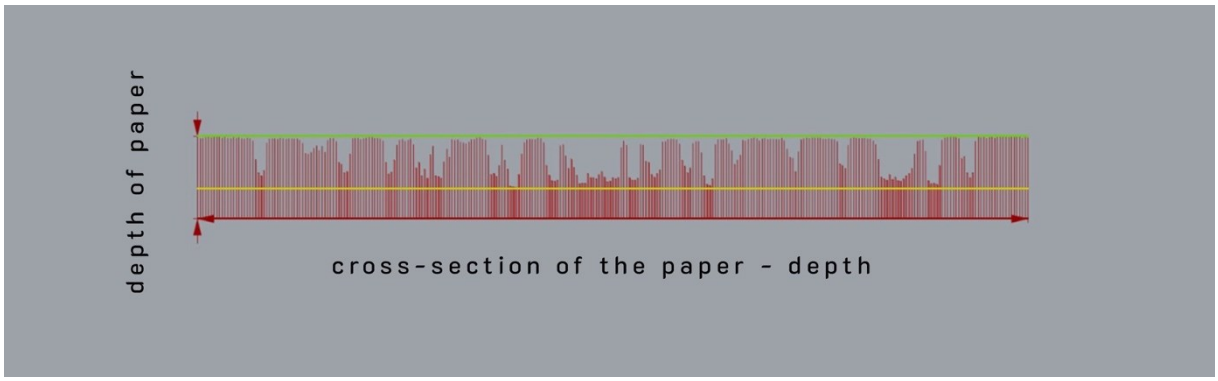


Figure 4. Visualization of the amount of coating agent applied to the background of the paper. Green line: top edge of the paper; red line (long arrow): base of the paper; yellow line: limit to which the coating agent layer thickness extends. This value ranges from 0 mm to 1 mm.

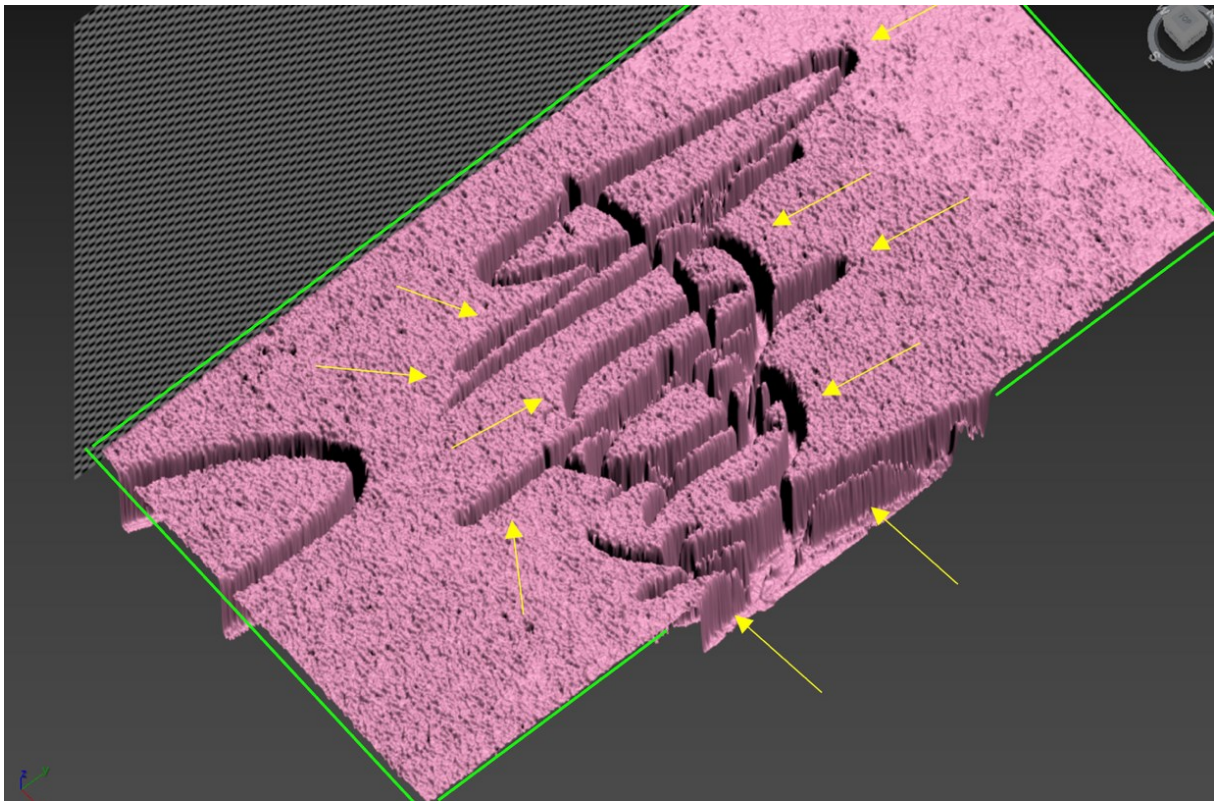


Figure 2. 3D model of the coating layer thickness in the base signature. Green line (border): top edge of the page. Arrows indicate the coating material (ink) thickness. Top view.

In the next stage, the output algorithm was extended with a script enabling comparative analysis of the coating thickness distribution of individual graphic structures in the grayscale (see Fig. 6).

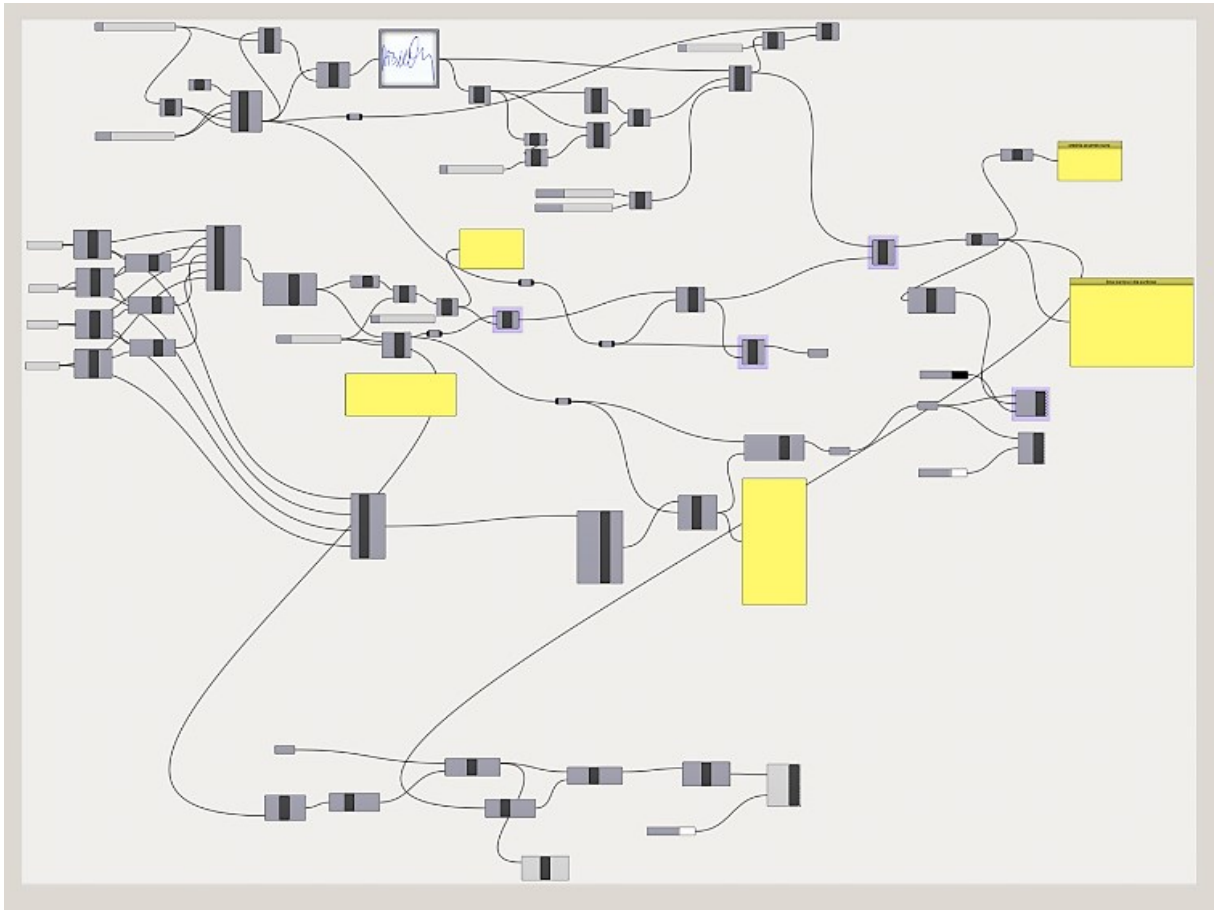


Figure 6. Script for analysing the coating thickness distribution on a grayscale.

At this stage, the analysis focused on four signatures produced by one of the co-authors, each written with a different ink layer. The thickness of the ink layer was automatically quantified by the program and represented as a spectrum. Each spectrum is based on differences in grayscale values corresponding to the scan brightness; for example, the grayscale can range from 0 to 100, with the range manually defined by the user. Consequently, the resulting spectrum of ink layer thickness reflects the corresponding grey saturation, with each original spectrum appearing in grayscale.

The methodology was as follows: first, each signature was scanned, and a separate grayscale spectrum representing ink layer thickness was generated for each. Second, for enhanced visualization, each spectrum was assigned a distinct color - red, blue, white, and green - and the colored spectra were then superimposed (see Figures 7 and 8).

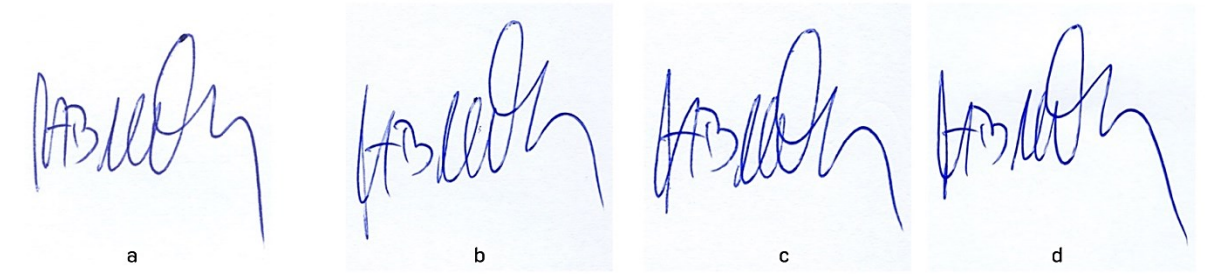


Figure 7. Signatures subject to analysis in grayscale - spectral colour designation; a. Red spectrum, b. Blue spectrum, c. White spectrum, d. Green spectrum.

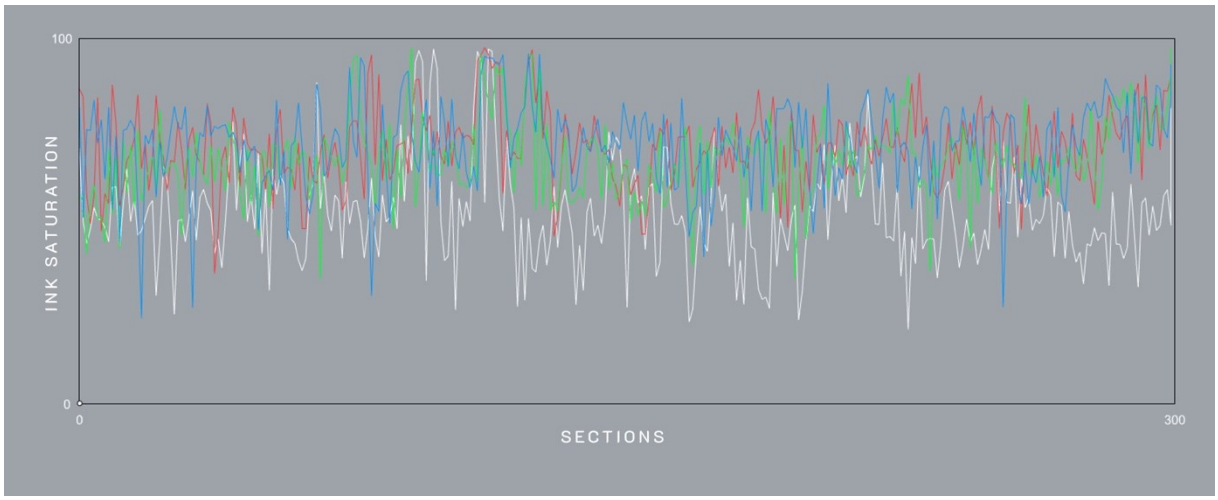


Figure 3. Superimposed image of spectra of signatures a, b, c and d.

Analysis of the spectra, focusing on the shape and distribution of peaks, indicates that the thickness of the covering material layer - a key pressure-sensitivity parameter - is highly consistent. A major advantage of the tested methods is the use of 3D visualization techniques, which provide significantly greater capabilities for displaying, analyzing, and presenting examined graphic structures compared to conventional methods commonly employed in judicial practice.

These techniques enable faithful reproduction of the graphic structure, preserving all proportions, details, and characteristics. Furthermore, through advanced lighting modelling, specular reflection, light dispersion, refraction, and shading solutions, many details that are difficult to capture using traditional handwriting analysis methods can be revealed, examined, and presented. This includes features related to both the texture of the substrate and the graphic structure itself. Additionally, once an accurate 3D model of the analysed graphic structure is created, further operations such as translation (moving the graphic in space), rotation, tilting, and scaling can be performed. Figures 9 and 10 illustrate two perspectives of the coating layer thickness visualization.



Figure 9. Image of the coating layer thickness relative to the sheet of paper in the form of an indentation.

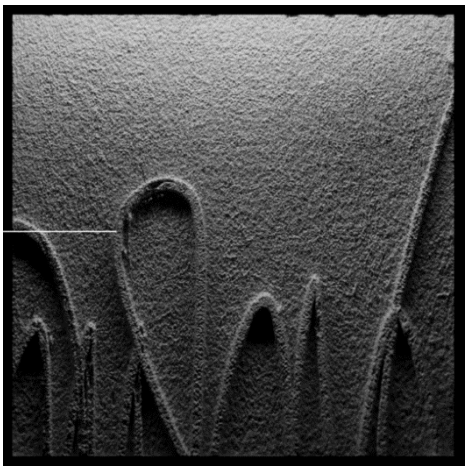


Figure 10. An inverted image of the coating layer thickness relative to the sheet of paper in the form of a convexity.

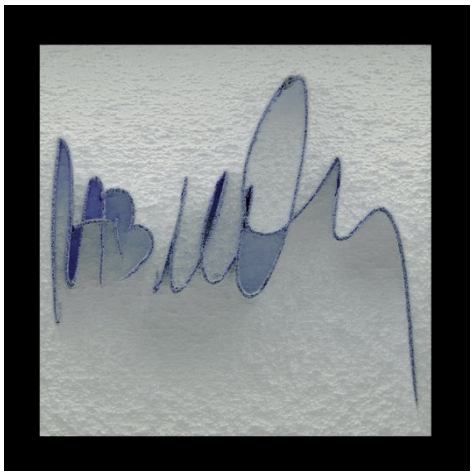


Figure 11. Visualization of a negative 3D model in colour.

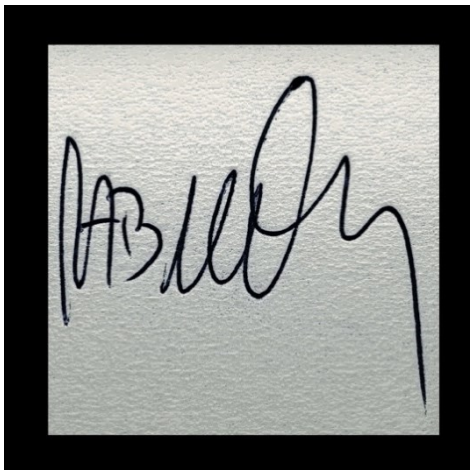


Figure 12. Visualization of a positive 3D model in colour.

Figures 11 and 12, in contrast, present a visualization of the signature analysed using the algorithm described in Figure 1.

3. Summary and conclusions

In summary, it should be emphasized that this research is of a pilot nature, and the algorithms described are still under development. At this stage, they cannot be considered fully validated tools for handwriting analysis. The authors aimed to explore the capabilities of digital technologies originally developed for purposes outside forensic identification, assessing their potential to form the basis of future supporting or alternative identification methods. To advance this work, more extensive experimental studies will be conducted using comparative materials from multiple individuals and a variety of ink types.

Based on the conducted research, the following conclusions can be drawn. The study demonstrated the extensive potential of applying modern digital techniques and 3D imaging tools, originally developed for architecture, in forensic handwriting and document examination. The algorithms developed by the authors are still under development and not yet ready for full implementation. Nevertheless, they represent a novel research direction, enabling the precise, numerical characterization of coating layer thickness distribution on a substrate. By providing a precise, numerical description of ink density distribution, these methods allow for accurate determination of handwriting parameters that are diagnostically important, which previously could only be described subjectively with vague terms such as “small”, “medium”, or “large” in reference to pressure force. The developed algorithms supply detailed information on features such as the shading of writing lines and the pressure exerted by the writing instrument on the surface. These characteristics are highly individualized, dependent on psychomotor abilities, and therefore critically important for personal identification. At the current stage, the tools are applicable to short graphic structures, such as legible signatures and initials, enabling analysis of both single signatures and comparative characteristics across multiple signatures. With further refinement and validation, the described algorithms could, in the future, be applied to broad population studies, not limited to forensic contexts, as a means of assessing individuals’ psychomotor performance.

This research represents a pilot, pioneering, and groundbreaking effort, constituting one of the first successful attempts to explore the application of architectural digital technologies in forensic handwriting analysis. The study demonstrates that such technologies can be effectively applied in forensic practice. It is anticipated that the use of digital technologies will continue to develop dynamically, offering new opportunities across multiple fields, including modern forensics. The authors are actively continuing their research in this area, and the coming years are expected to mark a period of significant growth for digital forensics.

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LABOUR MARKET POLICY IN POLAND IN THE LIGHT OF THE NEW LABOUR MARKET AND EMPLOYMENT SERVICES ACT: AN ANALYSIS OF SYSTEMIC CHANGE

Krzysztof GŁUC[1*], Krzysztof JUREK[2]

[1] Krakow University of Economics; gluck@uek.krakow.pl, ORCID: 0000-0003-0770-6789
[2] Jagiellonian University Doctoral School of Social Sciences; krzysztofjurek1@onet.pl, ORCID: 0000-0003-4154-6416
* Correspondence author

Purpose: The paper analyses the paradigm of the Polish labour market through a critical assessment of the Labour Market and Employment Services Act as a tool of labour activation policy. It indicates changes in mechanisms responding to challenges such as digitalisation, flexible employment, demographic shifts, and the importance of soft skills. At the same time, it identifies directions of institutional change for more effective activation and adjustment of labour policy to evolving socio-economic realities.
Design/methodology/approach: The study applies comparative analysis of the Act on Employment Promotion and Labour Market Institutions with the new Labour Market and Employment Services Act, combined with critical analysis of legal acts and strategic documents. The approach is interdisciplinary, integrating legal, economic, and social perspectives, with reference to labour market theory.
Findings: The analysis shows that the new Act introduces major changes in labour market functioning, though some areas remain unchanged. Research and literature review confirmed hypotheses and addressed research questions.
Research limitations/implications: Future studies should analyse the Act's implementation, focusing on its impact on labour office structures, service efficiency, and the use of labour market services. Empirical research including employees' and beneficiaries' perspectives is recommended to evaluate functioning and identify areas for modification.
Practical implications: The Act supports digitalisation, flexibility of enterprise support, and broader access to services. This should improve institutional efficiency, better match labour supply and demand, and increase professional activity with notable economic and social effects.
Social implications: The research offers insights for assessing legislative effectiveness and shaping social awareness of activation's role in economic transformation. Findings may inform flexible legal solutions that meet the needs of employers and job seekers. Modernisation of institutions also fosters public–private cooperation, contributing to higher quality of life through more effective services.
Originality/value: The article provides original scholarly value through a multidimensional analysis of the 2025 Act, combining legal, economic, and social perspectives. Its contribution lies in identifying directions of change as recommendations for legislators and practitioners,

supporting the adaptation of employment policy to contemporary challenges. The intended audience includes researchers, policymakers, and labour market practitioners.
Keywords: labour market policy; employment services; professional activation; legislative reform; Poland.
Category: Research paper.

1. Introduction

A natural stage in the life of most adults, following the completion or interruption of the educational process, is the commencement of professional activity. This stage plays a crucial role in achieving individual life goals, fostering personal development, and attaining financial independence. Entering the labour market, however, constitutes a significant challenge for many individuals, due to the existence of various barriers such as unstable employment conditions, limited job availability, or high competition. The labour market can be understood as the totality of all transactions of purchase and sale, together with their conditions and contexts, which determine the functioning of the system (Dębek, 2016). According to different criteria, markets may be classified by (Dębek, 2016):

- the object of exchange, distinguishing between markets for consumer goods and services and markets for production factors, such as land, labour, and capital,
- the degree of homogeneity of the transaction object, i.e., homogeneous markets and heterogeneous ones (for instance, the labour market, where different professions require diverse qualifications),
- the degree of price equalisation, i.e., perfect and imperfect markets,
- the market situation, i.e., a seller's market, reflecting excess demand, versus a buyer's market, reflecting excess supply,
- the geographical scope, encompassing local, regional, national, international, and global markets.

The concept of the labour market derives from classical economics, shaped in the 19th century during the formation of the market economy, and subsequently evolved under the influence of neoclassical, Keynesian, and contemporary economic theories. The labour market emerged as a distinct domain once human labour began to be treated as a commodity, which led to perceiving labour resources as a specific category of goods. This resource, however, is of a unique nature, as it consists of individuals endowed with "free will" and the capacity to make independent decisions. In the context of supply and demand relations, the value of this resource is expressed in the level of remuneration. Unlike machines or raw materials, labour resources exhibit autonomy, since employees can consciously decide whether to remain in employment or change employers. The labour market is marked by considerable dynamism,

manifested in constant transformations and the emergence of diverse socio-economic phenomena and interdependencies (Bania, 2017).

At present, the labour market is interpreted through a variety of economic theories, which are continuously modified and developed, drawing largely on neoclassical and Keynesian assumptions. These two schools often differ significantly, offering alternative, extended, or complementary sets of hypotheses concerning the occurrence, origins, and persistence of disequilibrium in the labour market. Consequently, interpretations of labour market phenomena and relations are frequently based on contrasting approaches of these two dominant traditions. Neoclassical and Keynesian theoretical frameworks thus constitute the foundation for analysing and explaining the functioning mechanisms and dynamics of the labour market (Dylkiewicz, 2014).

The neoclassical school of economics builds its theory of the labour market around two central research questions: the functioning of the market itself and the behaviour of individuals as participants in the transaction of buying and selling labour power. In the traditional neoclassical perspective, the labour market is conceived as a homogeneous and integrated system, where the allocation of labour is regulated by the price mechanism. In this context, the labour market functions as a space of exchange in which those offering work and those seeking employment meet, and the interactions between them determine both the level of employment and the level of wages.

In the economic literature, attention is also drawn to the concept of market equilibrium, understood as a theoretical, ideal state towards which the labour market tends, though unattainable in practice. Equilibrium assumes the confrontation of two groups of stakeholders: job seekers and employers offering vacancies. Moreover, there is a constant tension between employers seeking to hire labour at the lowest possible cost and employees expecting remuneration commensurate with their qualifications, experience, and skills. As a result, due to the natural competition on the supply side, two groups may be distinguished: the employed and the unemployed, both competing for available jobs. Employees aim to maintain their positions and market attractiveness, while the unemployed strive to secure employment. Supporting both groups are labour market institutions, which undertake activities aimed at mitigating the consequences of unemployment, promoting labour market activation, and fostering employment (Frączek, 2015).

One of the key contemporary public policies is state intervention in the functioning of the labour market. This stems primarily from the significant influence of labour market mechanisms on economic and social development, which are subject to dynamic and continuous transformations characteristic of this sector. Since such changes often generate substantial negative socio-economic consequences, state intervention in this domain becomes indispensable in order to minimise these effects and ensure the stability of the labour market system.

It is worth emphasising that the concepts of labour policy and employment policy are not synonymous, and the academic literature consistently distinguishes between them. Employment policy focuses on influencing the overall level of employment in a country, with particular emphasis on attaining full employment. The realisation of these objectives relies primarily on economic policy tools of a macroeconomic character, such as fiscal and monetary policies. Labour market policy, by contrast, primarily addresses structural problems and aims to enhance the efficiency of labour market functioning through the use of specialised instruments, such as training programmes, designed to align labour supply with demand. Unlike employment policy, labour market policy is characterised by a microeconomic approach, focusing on detailed aspects of labour market dynamics (Wiśniewski, 2020).

2. Methodology

The research methodology was based on the analysis of available sources concerning the labour market, both Polish and international, as well as on legislative changes introduced through the draft *Labour Market and Employment Services Act*. In the first stage, a detailed review of the literature was conducted, covering not only academic publications but also reports produced by public institutions. Subsequently, the method of document analysis was applied, which enabled the identification and evaluation of key changes in the legal provisions governing the functioning of the labour market (Krajewski, 2020).

The adopted approach was interdisciplinary, combining legal, economic, and social perspectives, which ensured a comprehensive view of the studied problem. This methodological framework allowed for the integration of theoretical insights with an assessment of practical regulatory changes. The research was exploratory in nature, aiming not only to verify selected assumptions but also to provide a basis for developing recommendations regarding future directions of labour market policy.

3. Labour Market Segmentation: A Historical and Theoretical Approach

The origins of unemployment are closely associated with the development of capitalism, while its wider dissemination dates back to the 19th century, when the number of industrial workers increased sharply. In the Polish context, unemployment remained relatively limited due to the small size of the industrial workforce and its strong ties to rural areas. In cases of job loss within the industrial sector, many workers would return, either seasonally or permanently,

to the countryside, where they engaged in various forms of agricultural labour. Others sought employment in industrial centres of the partitioning states, which further alleviated the negative consequences of unemployment on the domestic labour market. This pattern of seasonal and permanent migration was characteristic of the socio-economic conditions of that period and highlights a specific model of the labour market that combined both agricultural and industrial elements. Thus, while unemployment existed, it did not assume the form of a mass social problem that would later emerge during subsequent phases of economic development (Kłos, 2014).

Kwiatkowski, a distinguished Polish economist, argues that unemployment constitutes one of the most serious social issues of the 20th century, and there are strong grounds to believe that its significance will not diminish in the 21st century. The gravity of this phenomenon arises from its multidimensional nature: unemployment affects not only living standards and economic growth but also social attitudes and the public's evaluation of government effectiveness. Accordingly, unemployment should be treated simultaneously as an economic, social, and political issue. The diversity of definitions of unemployment stems from its complex nature and the multitude of research perspectives (Drela, 2015). Economists, policymakers, and sociologists approach this phenomenon in different ways, depending on their theoretical assumptions and analytical objectives. Each group emphasises distinct aspects—ranging from economic consequences, to social implications, to policy-related challenges (Głuc, Jurek, 2025).

According to the basic premise of labour market segmentation theory, the labour market does not operate as a uniform structure but rather exhibits significant heterogeneity on both the demand and supply sides. Consequently, it is possible to distinguish specific segments of the labour market that encompass jobs of a similar character and employees with comparable characteristics. The coexistence of similarities and differences among occupational groups and employers leads to the formation of market segments that function according to specific institutional rules, both formal and informal. In practice, this means that individuals aspiring to enter a given segment must meet certain access criteria, some of which are objective and beyond their control (e.g., age, gender, or ethnic background), while others relate to qualifications, work experience, or employment gaps. Depending on the segment in question, the balance between supply and demand may vary, resulting in both balanced and imbalanced market segments (Jurek, 2022).

From a theoretical perspective, the concepts of internal and external labour markets, as well as dual labour market theory, provide important insights into the sources and mechanisms of segmentation. These frameworks explain how the labour market is divided into structurally and functionally distinct segments. Such segmentation may manifest itself in differences in access to employment, job stability, wage levels, and career progression opportunities. Understanding the nature and mechanisms of segmentation enables policymakers to design more equitable and

effective instruments of state intervention. Accordingly, the analysis of segmentation processes becomes a key element in shaping effective labour market policy.

The distinction between internal and external labour markets highlights two separate segments. The internal labour market is characterised by employment stability, well-defined promotion pathways, limited entry opportunities for new workers, and regulated wage systems based on established norms and procedures. It also features a clear division of labour and detailed job classifications. While new entrants are admitted to the internal market, their access is usually restricted to the lowest levels of the promotional hierarchy. P. Doeringer and M. Piore identify three main factors shaping the formation and functioning of internal labour markets: unique firm-specific skills that are difficult to transfer to other employers, in-house training systems, and established customs concerning pay policies and the allocation of employees to specific positions (Zwiech, 2013).

For employers, the strategic goal is to ensure the appropriate qualifications of employees through targeted training. Initially, organisations invest in the professional development of their workforce and subsequently aim to maintain a stable staff base, thereby maximising returns on investment and reducing recruitment costs. Higher wages and greater employment security contribute to workforce stability, which in turn fosters the development of organisational norms and practices. Workers employed in the internal labour market do not compete directly with those from the external market, since access to the former is strictly regulated and limited (Jurek, 2023). By contrast, increases in overall employment are largely concentrated in the secondary sector, where employers tend to minimise costs associated with workforce turnover. Disadvantaged groups constitute a significant share of this sector, which is characterised by lower wages and limited promotion prospects (Jurek, 2023). Moreover, membership in the secondary sector is linked to restricted access to training opportunities provided at the workplace.

Scholarly debates also reveal divergences in views regarding the boundaries of labour market segments. Some researchers argue that segmentation occurs between firms, while others contend that it also exists within organisational structures. This situation is partly due to the fact that larger firms often outsource certain tasks to smaller firms in competitive sectors or employ workers on a part-time or temporary basis. In the context of dual labour market theory, key determinants of inequality include not only segmentation and specific candidate selection mechanisms but also training programmes and the persistence of real or perceived social roles. These factors influence employment interruptions and perpetuate unfavourable patterns for certain social groups and secondary labour market positions.

4. Labour Market Activation of the Unemployed

Labour market activation is defined as a set of activities aimed at maintaining balance within the labour market. The implementation of this task focuses primarily on individuals remaining without employment, who are offered support in job-seeking and skills enhancement, thereby facilitating their reintegration into the workforce. The concept also encompasses assistance for employers in recruiting suitable candidates for vacant positions. Activation processes are carried out by various labour market institutions, which employ both active and passive measures.

Active measures consist of direct actions supporting the unemployed in securing employment and assisting employers in finding appropriate personnel, with the overarching goal of preventing and reducing unemployment. This group of instruments includes, among others, job placement services, career counselling, internships, and training programmes (Szara, 2013). Contemporary socio-economic transformations emphasise the importance of shaping proactive attitudes and developing the capacity for employment or self-employment. Consequently, career guidance and counselling have become increasingly integrated into everyday practice. In light of dynamic labour market changes, rising competitiveness, challenges in career choice, and difficulties in securing employment or coping with unemployment, the assistance of professional career counsellors has become indispensable. As a result, the demand for advisory services designed to facilitate orientation and adaptation within the evolving labour market continues to grow (Krawczyk, 2014).

In Poland, supervision of career guidance is shared by the Ministry of Education and Science and the Ministry of Family and Social Policy. Both ministries define, through relevant legal acts, the scope of competences and responsibilities of institutions providing this form of support. This division of competences ensures a comprehensive approach to the organisation and functioning of career counselling across various levels and areas of social and educational policy. Accordingly, the Polish career guidance system is coordinated by multiple institutions working together to ensure effective assistance to individuals seeking support on the labour market (Wiśniewski, 2013).

Within the activities of labour offices, two main types of counsellors can be distinguished. The first group comprises professional career counsellors in the strict sense, whose primary task is to conduct counselling assessments and provide consultations to job placement officers. The second, far more numerous group consists of rank-and-file labour office staff, for whom counselling functions as an auxiliary role rather than an independent profession. In providing technical and informational assistance, these officials frequently extend support into areas of career planning, including psychological aspects. As a result, the scope of activity differs between the two groups in terms of both specialisation and the nature of the support delivered (Bańka, 1995).

Unemployed persons, employers, and employees may also benefit from a wide range of programmes co-financed by both European and national funds, which are intended to facilitate job placement, personal development, skills enhancement, and capacity building, as well as to strengthen the competitiveness of enterprises. A notable example is the set of regional programmes implemented in Polish voivodeships, financed under the European Funds for the period 2021-2027, which allocated over 33 billion euros to initiatives targeting labour market improvement and SME competitiveness. Within this framework, local labour offices (*Powiatowe Urzędy Pracy*) administer programmes designed for unemployed persons, employers, and employees alike, playing an essential role in fostering labour market participation and ensuring stability at the regional level (Strzeczak, 2007).

European Funds allocated to Poland for 2021-2027 are intended to promote labour market development and raise the skill levels of citizens. Implementation of diverse programmes fosters the advancement of particular regions. For instance, the programme *European Funds for Małopolska 2021-2027* draws on resources from the European Regional Development Fund (ERDF), the European Social Fund Plus (ESF+), and the Just Transition Fund (JTF). Within the labour market priority, seven key objectives have been established: improving access to employment and activation measures for jobseekers; promoting the balanced participation of women and men in the labour market; adapting workers and enterprises to ongoing transformations; ensuring equal access to high-quality education and training; promoting lifelong learning; facilitating the socio-economic integration of third-country nationals; and supporting marginalised communities in their socio-economic integration. These objectives reflect a comprehensive approach to labour market development and human capital formation (2004).

Job-seeking activities are often accompanied by high levels of stress for candidates; however, the contemporary labour market offers numerous solutions that mitigate these challenges. Job postings are widely available online—on forums, social networks, blogs, and thematic groups—which significantly simplifies access to potential opportunities. Employers also undertake diverse initiatives to attract the most suitable and skilled employees, thereby advancing company goals and fostering competitive, dynamic enterprises. On the other hand, jobseekers also hold expectations that extend beyond financial considerations. Increasingly, employees value respect, fairness, work ethics, the safeguarding of personal dignity, and the recognition of their contributions through rewards and acknowledgment. Rising levels of qualifications and knowledge have also translated into heightened demands regarding job type and conditions, which in turn shape new standards in employment relations (Dolot, 2018).

The job search process is a complex challenge for candidates, and the choice of appropriate forms and methods significantly affects their prospects of securing employment. Candidates must possess the ability to prepare effective application documents—such as curricula vitae and cover letters—and be familiar with the principles of successful self-presentation, which are

indispensable for progressing beyond the initial recruitment stage. Job search strategies can be divided into passive and active methods. Passive methods, such as reviewing job advertisements or registering with labour offices, require limited engagement and are relatively less time-consuming. Active methods, in contrast, demand greater initiative, including personal visits to firms, participation in job fairs, or networking activities. An active approach substantially increases the likelihood of finding employment, as it facilitates more direct interaction with potential employers. Therefore, the effective combination of both approaches can yield the best results in job seeking (Mazur-Mitrowska, 2018).

5. Changes in the Labour Market Activation of the Unemployed

The new *Labour Market and Employment Services Act* is a comprehensive document exceeding 300 pages, affecting multiple groups directly and indirectly engaged in labour market functioning and the formal-legal processes associated with its implementation (2025). The proposed reforms cover a wide range of regulatory areas and labour market operations, aiming to strengthen the state's capacity to promote employment, mitigate the consequences of unemployment, and enhance labour market activation. These tasks are pursued through both public and non-public labour market institutions that support individuals struggling to secure or retain employment, as well as employers seeking qualified workers. In 2023, more than 2.5 million people made use of labour office services.

The structure of public employment services encompasses 16 regional labour offices (*wojewódzkie urzędy pracy*, WUP), subordinated to provincial marshals, and 340 district labour offices (*powiatowe urzędy pracy*, PUP), subordinated to county governors. This system, operational since 2000, follows a central–local governance model, in which each organisational unit retains autonomy. By the end of 2023, WUPs and PUPs employed a total of 20,145 staff members. Notable problems in this sector include excessive administrative workload and a shortage of qualified personnel—challenges that the new legislation seeks to address. For example, in some PUPs, the caseload per career counsellor ranged from 113 to as many as 2571 registered unemployed individuals. Similarly, the number of unemployed per job placement officer varied from 43 to 891, and per frontline client service worker from 29 to 367. Such disproportionate caseloads hinder the ability of staff to devote adequate attention to individual clients and to reach out effectively to the economically inactive population. This underscores the urgent need for reforms that align with the evolving requirements of both employers and employees in the labour market.

The necessity of introducing the new Act was justified by the structural challenges facing the labour market, one of the most pressing being the low level of economic activity. In the fourth quarter of 2023, approximately 3.8 million working-age individuals were inactive,

meaning they did not participate in the labour market. This group is highly diverse in terms of reasons for inactivity, but it is essential to reach and support them in their return to employment. Economically inactive persons constitute an untapped reserve of labour resources, with significant potential to contribute to economic growth. Their effective activation is crucial for increasing both the activity rate and the employment rate in Poland, particularly given the projected decline in the working-age population in the coming years.

Reforms concerning support for individuals under 30 years of age focus primarily on assessing digital competencies at the time of registration as unemployed or job-seeking. Each PUP is staffed with an employment advisor dedicated to young people, allowing for a more individualised and effective response to their labour market needs. Moreover, young unemployed individuals may access educational loans of up to four times the average monthly wage. These funds may be allocated to various educational purposes, such as paying for training courses, postgraduate studies, skills certification, or obtaining documents necessary for continuing formal education. Importantly, up to 20% of the loan may be forgiven. Additionally, the existing relocation allowance (*bon na zasiedlenie*), previously reserved for individuals under 30, has been extended to all unemployed persons regardless of age, reflecting growing demand for this form of support among older groups.

The reforms also extend access to support measures provided by PUPs to family micro-enterprises, regardless of kinship between the unemployed client and the employer. This adjustment eliminates previous barriers that limited assistance for family businesses, thereby supporting their development and, in the long term, contributing to job creation and local labour market stability.

Further changes include raising the age of a disabled child for whom a county governor may reimburse childcare costs, from the previous limit of 7 years to 18 years. Currently, reimbursement applies only to children under 6 years of age and disabled children up to 7 years of age. The method of calculating benefits for socially useful work has also been revised, with the new amount set at 44% of the minimum hourly wage. The loan ceiling for establishing a workplace has been raised from six times to ten times the average wage, with up to 25% of the funds allowed for employee-related costs. The mandatory period for maintaining subsidised workplaces has been shortened from 24 months to either 12 or 18 months, depending on the circumstances.

As a result of these changes, the practice of referring unemployed persons to private employment agencies will now extend to all registered jobseekers, not only those facing the most difficult labour market situations. Furthermore, the remuneration for agencies maintaining long-term unemployed individuals or youth under 30 in employment has been raised from 150% to 200% of the base rate, provided that the employment lasts at least 180 days within a 240-day period from referral. Given the significant distance of these groups from the labour market, intensified support and tailored reintegration mechanisms are essential. Similarly,

intervention work programmes for youth under 30 are preserved, offering employment for 3 to 12 months, with the requirement that jobs be retained for a period equal to the subsidy duration.

Employment advisors are now required to conduct individual interviews with every person registering at a PUP, aimed at diagnosing their life circumstances, needs, and potential labour market participation. Continuous professional development of both career counsellors and employment advisors has also been prioritised, with training programmes designed to raise their competencies. This effort seeks to build a highly skilled workforce capable of effectively identifying and responding to local labour market needs. Moreover, the scope of career counselling responsibilities has been expanded to include PUP staff who, while not formally recognised as career counsellors, possess the necessary qualifications to provide such services, thereby increasing the accessibility of counselling.

Collaboration between WUPs and PUPs with schools, universities, and social economy entities engaged in career counselling has also been strengthened. Another important reform is the obligation for public entities, state-owned companies, and organisations managing public assets to submit job offers to the central job database, with certain exemptions granted due to operational specificities. This database is managed by the Ministry of Family and Social Policy through the *ePraca* portal (formerly the Central Job Offers Database, CBOP). Posted job offers must include details on employment conditions, employer characteristics, and candidate requirements. The system also verifies whether the employer has outstanding social security or tax liabilities exceeding two months; if so, the posting is blocked and redirected to the relevant PUP for review. This mechanism aims to curb abuse and protect jobseekers. The introduction of automated candidate–job matching is also expected to shorten job search times and improve labour market efficiency.

Unemployed members of large families holding a Family Card (*Karta Dużej Rodziny*) and single parents raising at least one child are now given priority in access to support measures under the new Act. Additionally, caregivers of disabled persons, who were previously excluded from many support instruments, are now entitled to the same benefits and services as other unemployed persons, thereby significantly expanding their rights.

Major changes have also been introduced in the technical functioning of labour offices, particularly through the modernisation and automation of client services via the online platform *praca.gov.pl*. This innovation enables clients to handle numerous matters remotely, such as checking their registration status, selecting appropriate training programmes, browsing job offers, reviewing individual action plans, and communicating with assigned advisors. The digital system also allows users to prepare and share CVs, apply for support measures, and access thousands of job postings listed on *ePraca*. Clients may also update their data concerning cooperation with the labour office entirely online.

6. Discussion

The reforms introduced by the new *Labour Market and Employment Services Act* aim to enhance both the accessibility and the effectiveness of available forms of assistance for the unemployed. Priority treatment for jobseekers from large families and for single parents with dependent children reflects an increased awareness of the needs of groups particularly vulnerable to social exclusion. At the same time, the expansion of support to caregivers of persons with disabilities demonstrates a commitment to a more inclusive approach toward system beneficiaries. Aligning their entitlements with those of other unemployed individuals helps to reduce inequalities in access to public support.

Furthermore, the introduction of comprehensive "activation packages" and programmes such as *internship plus* increases the likelihood of sustainable employment by integrating multiple forms of support. Equally important is the focus on young people under the age of 30, which includes the assessment of digital competencies and the possibility of accessing educational loans. These measures directly address the challenges of today's labour market, in which digital skills and lifelong learning are increasingly essential.

The reforms also highlight the need to adapt employment policy to the dynamic socio-economic environment. Expanding the role of employment advisors and investing in the professional development of PUP staff enhances the capacity to deliver services tailored to individual client needs. The modernisation of job placement processes through digital tools—particularly automated candidate–job matching systems—underscores the growing significance of technology in labour market management.

Equally noteworthy is the expansion of registration opportunities, which allows unemployed persons to register at any labour office, thereby removing administrative barriers and facilitating easier access to support services. This flexibility, combined with new mechanisms for workplace creation loans, reimbursement of childcare costs for children with disabilities, and more flexible subsidy conditions for employers, reflects a broader effort to increase both the inclusivity and the efficiency of labour market activation instruments.

Taken together, these legislative changes represent a comprehensive step toward a more inclusive and effective labour market policy. By focusing on disadvantaged groups, integrating technological innovation, and broadening institutional cooperation, the reform addresses the structural weaknesses of the Polish labour market and provides a framework for adapting to ongoing economic and demographic challenges.

7. Conclusions

The analysis conducted allows us to conclude that the new *Labour Market and Employment Services Act* has introduced significant changes both in the functioning of District Labour Offices (*Powiatowe Urzędy Pracy*, PUP) and in the scope of assistance provided. These reforms are primarily focused on increasing the effectiveness of career counsellors' activities and on adapting support instruments to the current needs of the labour market.

The digitisation of services and the expansion of access to career counselling contribute to more efficient client service and to higher levels of professional activation. Moreover, the extension of the beneficiary group to include farmers and economically inactive individuals reflects the growing commitment of labour market institutions to inclusivity and individualised support.

Changes concerning reimbursement conditions and support for family micro-enterprises further illustrate the pursuit of a multidimensional approach to labour market activation. In effect, the new legislation addresses the challenges of the contemporary labour market with the dual aim of improving the quality of public services and enhancing the overall effectiveness of employment policy in Poland.

At the same time, the solutions introduced establish a framework for further development and adaptation of the support system to evolving economic and social conditions. This forward-looking orientation indicates that the Act should be seen not as a final stage of reform, but as a foundation for continued innovation in labour market policy. Future trajectories may include, for instance, the gradual integration of artificial intelligence into employment services to personalise support, the development of lifelong learning frameworks aligned with digital transformation, or the creation of targeted instruments for groups most vulnerable to automation and demographic change. Another possible direction is the expansion of public–private partnerships in vocational training and reskilling initiatives, enabling closer alignment between labour supply and employer demand.

Such scenarios highlight that the long-term value of the Act will depend not only on its initial provisions but also on policymakers' capacity to use it as a platform for adaptive, evidence-based strategies responding to structural shifts in the Polish and European labour markets.

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UNIVERSAL BANKS IN EU CEE COUNTRIES IN 2019-2023 – COMPARATIVE ANALYSIS

Maciej GONISZEWSKI

University of Gdańsk; maciej.goniszewski@ug.edu.pl, ORCID: 0009-0002-4462-271X

Objective: The objective of this study is to ascertain the impact of two significant global shocks on the universal banking sectors of Central and Eastern European (CEE) countries: the emergence of the novel coronavirus (SARS-CoV-2) and the outbreak of war in Ukraine. The study will examine how countries' responses to these shocks, as measured by profitability, efficiency, and the volume and quality of loans, vary across different geographical locations and degrees of internationalisation of banking sectors.
Project/methodology/approach: The study constitutes an empirical investigation that employs quantitative methodologies, drawing upon secondary data sourced from the Orbis database. The research process comprised the following stages: a review of the extant literature, the grouping of the analysed sectors according to their degree of internationalisation, a descriptive study of universal banking sectors, a synthesis of indicators, a comparative analysis, a study explaining the variation in results.
Results: A comparative analysis of universal banking sectors in CEE countries indicated that a greater influence of political factors on the banking sector of a given country was associated with greater volatility in bank profitability and lower efficiency. It was also highlighted that the Polish banking sector attained the most unfavourable results in the region. The study did not confirm the hypothesis that in the CEE region, the distance of a given country from the participants in the conflict in Ukraine is important for the performance of the banking sector.
Research limitations/implications: The objective of the present study was to furnish a preliminary overview of the issue, for which the researcher primarily employed descriptive methods and comparative analysis. The subsequent stage in the research process could involve the utilisation of statistical analysis tools and econometric models.
Practical implications: This may be a significant contribution to the ongoing discourse on the accession of CEE countries to the eurozone and the legitimacy of substantial state capital involvement in the banking sector.
Originality/value: To the best of the author's knowledge, this paper presents the results of the first study comparing the financial performance of universal banking sectors in CEE countries during the pandemic and the outbreak of war in Ukraine.
Keywords: bank, state ownership, Covid-19, war in Ukraine, CEE countries.
Type of work: research article.

1. Introduction

The initial phase of the 2020s constituted a period of two robust impulses that exerted influence on the economies of the erstwhile communist countries of Central and Eastern Europe, which are members of the European Union. The initial event was the onset of the Coronavirus pandemic, which resulted in the cessation of economic activity by numerous economic entities. The second was the outbreak of war in Ukraine, which caused a decline in investor confidence in the markets neighbouring the parties to the conflict and an influx of refugees from Ukraine. Numerous studies have confirmed the significant impact of both phenomena on the banking sector in these countries (Miklaszewska et al., 2021; Doran et al., 2022; Kozak, 2021; Węgrzyn, Topczewska, 2023; Badics, 2023; Karaś, Boda, 2024).

However, the banking sectors of these countries are currently quite diverse in terms of the size of the financial sector in relation to the country's economy, the ownership structure of the banking sector – domestic capital, foreign capital, private capital, state capital – and the monetary policy that shapes the operating conditions of banks – some countries belong to the eurozone, while others pursue their own monetary policy. This diversity implies that, in certain countries, banking sectors are subject to heightened influence from local authorities and supervisory institutions, while in others, this influence has been predominantly transferred abroad. It is important to note that not all countries in the region border the participants in the conflict that broke out in 2022. This may be a factor differentiating the banking sector's response to the second of the analysed impulses.

The aim of this paper is to compare the reactions of individual national banking sectors in EU countries neighbouring the parties to the conflict in Ukraine to both the Covid-19 pandemic and the outbreak of war in Ukraine, and to analyse whether there is a link between the banking sector's greater dependence on foreign institutions and its reaction to strong external shocks. It will also be examined whether, within the CEE region, there is a noticeable variation depending on geographical distance from the war in Ukraine.

The study will test two hypotheses that can be formulated on the basis of previous research. The first hypothesis concerns the significance of geographical distance from the conflict for the strength of the shock to which the banking sectors were subjected in 2022.

A certain investigation into the repercussions of the Russian-Ukrainian war on the financial sector suggests that geographical proximity exerts a significant adverse influence on markets and banking institutions. In their 2024 study, Federle, Meier, Müller and Sehn present the so-called "penalty for proximity", which posits that an increase in the distance from Ukraine of 1000 km is associated with a 2.6 percentage point increase in stock market returns. In a similar vein, Silva, Wilhelm and Tabak (2023) posit that in Europe, the strength of the reaction was predominantly determined by proximity to the conflict itself, as opposed to trade per se. Pham, Talavera and Tsapin (2018) present evidence for banks from the period of hybrid warfare

following the annexation of Crimea and eastern Ukraine, prior to the onset of full-scale war. Their findings indicate that in regions of Ukraine closer to the front line, there was a more pronounced deterioration in the quality of bank assets and a reduction in credit.

However, it should be noted that not all analyses support this relationship. As Martins, Correia and Gouveia (2023) demonstrated, European bank share prices declined principally as a function of their exposure to Russia, rather than geographical distance alone. De Haas, Mamonov, Popov and Shala (2025) also found no evidence of credit shocks spilling over to neighbouring countries – international banks reduced their financing of the country affected by the conflict, but did not increase or decrease it in neighbouring countries.

Notwithstanding the equivocal outcomes of the study, the first hypothesis posits that geographical proximity is a salient factor, and that banking sectors in Central and Eastern European countries that share borders with Ukraine and Russia demonstrated a more pronounced response in terms of fluctuations in profitability, efficiency and lending when compared to countries CEE that do not border the conflict participants.

The second hypothesis pertains to the diversity of banking sectors within the CEE region in relation to their reliance on the decisions of foreign institutions. It can be hypothesised that those sectors which are more globalised and dependent on decisions made abroad will exhibit a greater degree of dynamism in their reaction to global external stimuli, such as a pandemic or war. This argument was advanced by Polish politicians and some economists in the aftermath of the global economic crisis triggered by the collapse of Lehman Brothers. The call for the repatriation of banking operations in Poland from foreign to domestic capital was a key demand. Such a buyout did take place, but the acquisition was executed by state capital rather than by private capital. This has resulted in a significant degree of dependency within the banking sector of the country on the actions and influence of politicians. This scenario has the potential to result in bank management boards arriving at decisions that are advantageous to the government, but not necessarily to the bank itself. A review of research on the impact of foreign and state capital on the condition of banks during crises, as well as research in this area, is available in the publication "Foreign Capital in Banks" (Goniszewski, 2023). The findings of these studies are diverse and contingent on numerous factors. However, the majority of researchers concur that financial institutions under state control are most susceptible to suboptimal decision-making during periods of crisis. Consequently, the second hypothesis posits that the universal banking sectors of CEE countries, which are more dependent on the decisions of domestic institutions, exhibited diminished profitability and efficiency during the pandemic crisis and the subsequent shock following the outbreak of war in Ukraine. This decline in performance was accompanied by a contraction in lending, and an escalation in the share of non-performing loans.

The subsequent section of the article will provide a review of research on the impact of the pandemic and the outbreak of war on the banking sector. The third part will describe the data that was utilised and the research methodology. The fourth part of this study will group the

banking sectors of countries bordering the participants in the conflict based on characteristics describing their degree of globalisation. The individual banking sectors analysed will be described, and their condition in 2019-2023 will be outlined. Finally, a comparison of the average results achieved by individual sectors and the dynamics of changes in the value of indicators in key years will be made. In the fifth part, the results obtained will be compared with those of previous studies conducted in this area. The summary will present the conclusions of the study and, on their basis, verify the hypotheses set out in the introduction.

2. The banking sector and the pandemic and war – literature review

2.1. Assessment of the impact of the Covid-19 pandemic on the banking sector

The onset of the Coronavirus Disease 2019 (Covid-19) pandemic, in conjunction with the restrictions imposed by governments on the operations of economic entities in 2020, precipitated a precipitous escalation in uncertainty concerning the subsequent evolution of the global economic landscape. This phenomenon is reflected in the Global Economic Policy Uncertainty Index (GEPU), the values of which are presented in Figure 1. At the beginning of 2020, it reached its highest value in history. Not even the subsequent war in Ukraine engendered such a level of anxiety, and a similar level was only reached by Donald Trump's first decisions in his second term in early 2025.

The GEPU index is a weighted average of national economic policy uncertainty (EPU) indices for 21 countries: The following countries are represented: Australia, Brazil, Canada, Chile, China, Colombia, France, Germany, Greece, India, Ireland, Italy, Japan, Mexico, the Netherlands, Russia, South Korea, Spain, Sweden, the United Kingdom and the United States.

Analogous indices are also created for other countries. In Central and Eastern Europe, among the countries that share borders with Russia and Ukraine, Poland is the sole nation to possess such a facility. As demonstrated in Figure 2, the scale of uncertainty in the region is distinct from the global scale. The primary distinction pertains to the index level at the time of the pandemic's onset and the commencement of the war in Ukraine. This suggests that the economic impact of these two factors, including their effect on the banking sector, was comparable in this region.

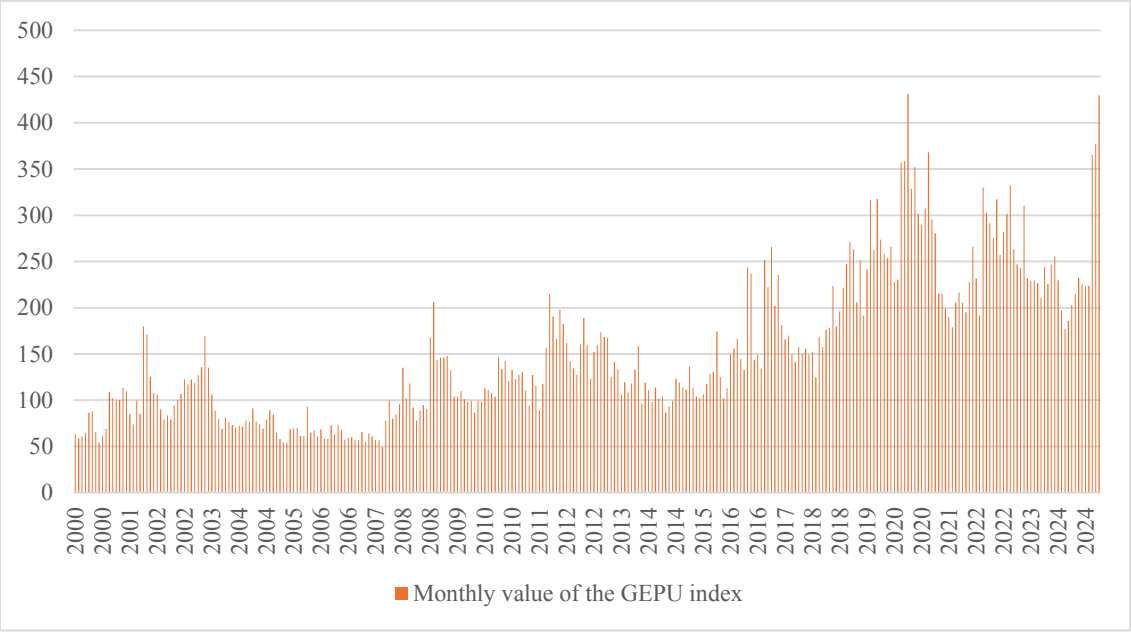


Figure 1. Global Economic Policy Uncertainty Index (GEPU) in 2000-2025.

Source: Global Economic Policy Uncertainty, Retrieved from: https://www.policyuncertainty.com/, 4 May 2025.

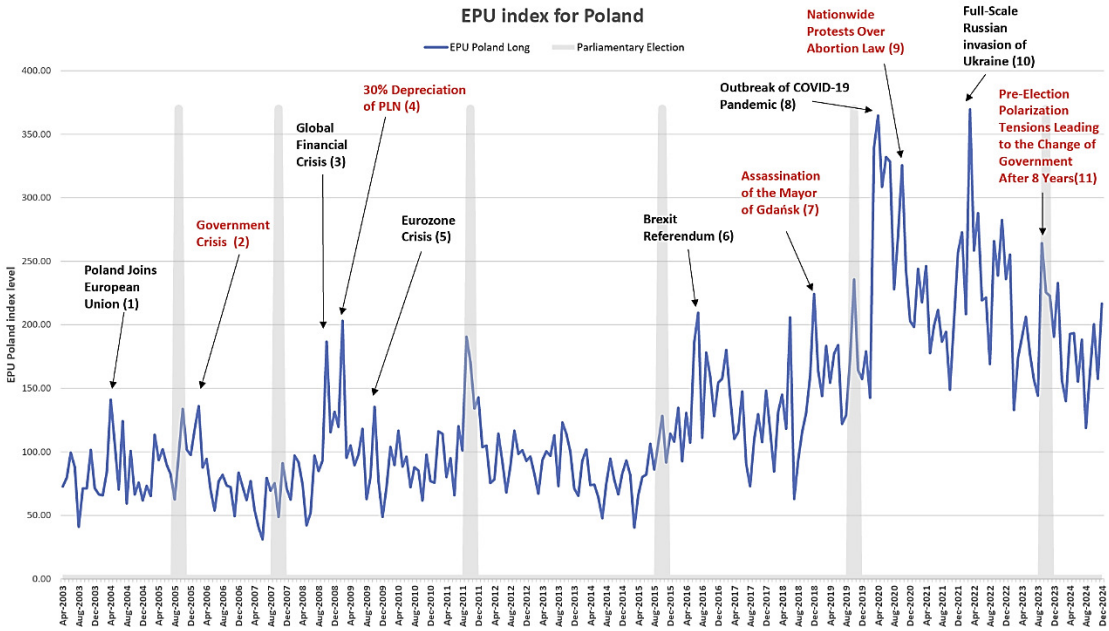


Figure 2. Economic policy uncertainty index for Poland in 2003-2025.

Source: Local and External Economic Policy Uncertainty and Their Impact on Exchange Rates in Emerging Markets: Evidence from Poland by Jędrzej Białkowski, Rafał Klepka, and Anna Sławik, available at SSRN: http://dx.doi.org/10.2139/ssrn.5104696

The primary factor contributing to the prevailing uncertainty surrounding the future of the economy subsequent to the pandemic's onset was the implementation of comprehensive lockdowns by governments, which entailed the prohibition of citizens from leaving their residences and direct business operations by entities across numerous sectors. This has given rise to concerns regarding the financial survival of entities lacking current revenues, and in the

initial stage, reduced consumption has resulted in diminished demand for credit (Goniszewski, 2024).

2.2. Assessment of the impact of the outbreak of war on the banking sector

The war in Ukraine, in which a nuclear power is involved, has caused one of the two highest increases in uncertainty in the global economy, as indicated above. The most significant concerns pertained to the energy and food sectors (Kurzeja, 2022), consequently, the war had ramifications for all sectors of the economy, including the banking sector, through increases in energy and food prices.

Nevertheless, the global impact on the banking sector was not only a consequence of uncertainty, but also a direct result of the sanctions imposed on Russia. These included US sanctions prohibiting the Central Bank of Russia from using the US dollar for payments. This decision effectively rendered all reserves of the Russian government and its citizens held in US dollars inaccessible, resulting in losses for domestic and international banks. The prohibition on Russian financial institutions utilising the SWIFT network has resulted in the restriction of financial payments within the global banking sector, specifically between Russian consumers and companies, and other traders worldwide. A further restriction was the withdrawal of Visa, MasterCard, American Express and PayPal services from the Russian economy, which also resulted in a decline in the revenues of international banks (He, 2022).

The war in Ukraine had a more complex impact on the banking sector in countries bordering the parties to the conflict. In addition to the aforementioned factors resulting from sanctions related to the banking system, the war also affected the banking sector through stock exchanges, which recorded more sustained declines in share prices than in countries further away from the conflict, and through higher inflation, which was significantly influenced by the increase in energy and agricultural commodity prices, which in these countries came largely from Russia and Ukraine (Borowski, 2022). In the context of the present conflict, it has been observed that countries which are directly adjacent to the site of hostilities have experienced a more dynamic weakening of their local currencies against the euro than those countries which do not share a border with the site of hostilities, to occur even in cases where the economies of the two countries are strongly correlated with each other. For example, there has been a strong weakening of the currency in Poland and Hungary, and a weaker one in the Czech Republic (Mielus, 2022).

An investigation was conducted by Marta Karaś and Michał Boda (2024) into the repercussions of the war in Ukraine on the fiscal soundness and stability of banking institutions in Central and Eastern European countries that share a border with the nations embroiled in the military engagement. The study revealed that the war did not cause a deterioration in the capital ratio of the banks surveyed. However, it did affect other indicators of stability and financial condition. These findings suggest that in times of war, the banking sector may respond with increased uncertainty and greater sensitivity to risk, and focus on safer investments.

Furthermore, the war may have exacerbated mistrust of the banking sectors in countries where these sectors have developed relatively recently – compared to Western Europe – and where a serious money laundering scandal occurred just two years before the outbreak of the war. Between the years 2018 and 2020, the Baltic states demonstrated a failure to implement the relevant measures concerning the prevention of money laundering. This failure is evidenced by the detection of such activities at Ukio Bank in Lithuania, ABLV Bank in Latvia, and Danske Bank in Estonia. The latter case involved the largest amount – USD 200 billion in illegal funds from Russia. The prevailing apprehension among Western analysts regarding the stability of Eastern European banking markets in the context of Russia's expansionist policy was articulated in the article by Katarzyna J. McNaughton of Queen's University in Ontario, Canada. The Canadian researcher writes: "The three Baltic countries are not representative of FIUs in general, but rather share being small, post-Soviet countries that are likely to be the first targets of future Russian illicit money, cyber, and economic aggression. It is probable that future Russian military aggression into the Baltics will be preceded by various attempts to undermine the stability and integrity of the Baltic's financial and economic systems" (McNaughton, 2024, p. 2).

3. Data and methods

The study incorporated profitability, efficiency and credit portfolio quality indicators obtained from the Orbis database for universal banks operating in seven UE countries bordering Russia and Ukraine: The countries in question are Estonia, Latvia, Lithuania, Poland, Slovakia, Hungary and Romania. The total number of banks included in the study is 66, including: eight Estonian, nine Hungarian, four Lithuanian, four Latvian, eighteen Polish, fifteen Romanian and eight Slovakian. Furthermore, the average score of universal banks from the Czech Republic and Bulgaria was included, as these countries have the most similar history of banking sector development to the main group analysed, but do not directly border the countries involved in the conflict. A total of 27 banks from these countries were included in the study was 27, with 16 originating from Bulgaria and 11 from the Czech Republic. The inclusion of these variables was intended to ascertain whether the proximity to armed conflict exerts an influence on the levels of the analysed indicators.

It should be noted that the present study exclusively encompasses universal banks. This restriction is intended to eliminate differences resulting from the specific nature of the activities of development banks and specialist banks.

The study's scope excluded banking institutions that experienced bankruptcy during the period 2019-2023, as well as those initiating or concluding their operations during this time. Additionally, institutions that did not disclose financial results or those whose universal

operations exhibited a marked deviation from the market average in terms of the indicators characterising their activities were also excluded from the study. Due to the aforementioned reasons, the study excluded four Polish banks, three Romanian banks, and one Estonian and one Lithuanian bank.

The following banking institutions were not included in the group of Polish universal banks: Bank BPH was omitted from the analysis due to the paucity of information regarding this financial institution in the Orbis database, which serves as the primary data source. The other institutions not included in the study were Bank Nowy, which was undergoing a restructuring process during the period under scrutiny; Getin Noble Bank, which was in bankruptcy at the time; and Velo Bank, which was established during the compulsory restructuring of Getin Noble Bank. In view of the paucity of information in the Orbis database, the Estonian Holm Bank, the Romanian Patria Bank and TechVentures Bank were also excluded from consideration.

The study also did not include the Romanian Banca Romana de Credite si Investitii, which generated losses throughout the analysed period. This was due to the very specific nature of its business, which focused on providing banking services to small and medium-sized enterprises and a selected segment of retail and private banking customers. Consequently, it was not a conventional universal bank. (BRCI, 2024).

The non-standard nature of its activities was also the reason for not including Lithuania's Revolut Bank, which is, firstly, a financial technology company – a so-called fintech – and, secondly, operates mainly outside its home market.

The present study constitutes an empirical investigation that employs quantitative methodologies, drawing upon secondary data sourced from the Orbis database. The data set encompasses profitability and efficiency indicators, as well as metrics delineating the credit policy of the individual banks under scrutiny. The profitability indicators included in the study are return on equity (ROE) and return on assets (ROA). The efficiency of the system was assessed using the cost-to-income ratio (C/I) and the net interest margin (NIM). The quality of the loan portfolio was assessed using the loan-to-deposit ratio (L/D) and the non-performing loan ratio (NPL).

The research process involved a descriptive study of the universal banking sectors in individual countries, using a set of the above-mentioned indicators for the years 2019-2023, as well as available scientific literature and economic reports from national and international supervisory institutions. In addition, the indicators were synthesised by calculating average values and the dynamics of changes in average values in order to obtain synthetic values for individual national banking sectors.

The indicator values for entire sectors obtained in this way were then subjected to a comparative analysis to identify the countries where banks achieved the highest and lowest profitability and efficiency, and countries where lending was growing or declining in relation to deposits, and countries where the quality of the loan portfolio was improving or deteriorating.

The final step in the research process was to conduct a study explaining the variation in results. The variables used to explain the differences were: the distance of a given country from the theatre of war (only in relation to the impulse provided by the war in Ukraine) and the degree of internationalisation of a given banking sector.

4. Results

4.1. Characteristics of the degree of internationalisation of the banking sectors in CEE countries

Despite the fact that the group of countries analysed has experienced a transition from a socialist to a free market economy over the past 30 years, the banking sectors of these countries have developed in a diverse range of ways, as reflected in the financial institution development index created by the International Monetary Fund. The index is formulated to encompass a range of relevant metrics, including private sector debt in relation to GDP, the presence of bank branches, and the number of ATMs per 100,000 adult citizens. Additionally, it considers key financial indicators such as net interest margin, credit-deposit spread, and ROA and ROE (Marcinkiewicz, Kuzionko-Ochrymiuk, 2024). With regard to the values of the indicators presented in Table 1, the analysed group of countries can be divided into three subgroups. Countries with the least developed financial institutions – these are the two Baltic states: Lithuania and Latvia; countries with average development of financial institutions – Estonia, Romania and Poland; and countries with the highest level of development of financial institutions – Slovakia and Hungary.

Table 1.
Financial Institutions Index 2021

Country	FII value
Lithuania	0.358
Latvia	0.382
Estonia	0.444
Romania	0.469
Poland	0.483
Slovakia	0.525
Hungary	0.527

Source: Own study based on data from DBnomics, https://db.nomics.world/IMF/FDI?tab=list

All countries in the region underwent a process of development and modernisation of their banking sectors, which was facilitated by the inflow of foreign capital. However, in the aftermath of the global financial crisis, a few of these countries opted to curtail the allocation of this capital in favour of domestic capital. The consequence of these actions is the current diversity in this area, presented in Table 2. Hungary and Poland are countries in this

group where domestic capital predominates in the banking sector. In the case of Romania and Latvia, foreign capital predominates, but domestic capital also has a significant share. In contrast, in Estonia, Lithuania and Slovakia, domestic capital accounts for a comparatively negligible percentage of the banking sector's capital.

Table 2.
Share of foreign capital in banking sector assets in 2023

Country	Share of FC %
Hungary	33
Poland	42
Romania	66
Latvia	76
Estonia	85
Lithuania	90
Slovakia	95

Source: Own study based on data from: The European Banking Federation: https://www.ebf.eu/facts-and-figures/country-by-country-overview/, Banku sektora transformācija Eiropas Savienībā un Ziemeļeiropā un tās ietekme uz sektora konkurenci Latvijā, https://www.ekonomisti.lv/wp-content/uploads/2024/06/Banku_petijums.pdf, Information on the situation of the banking sector in 2023; Financial Supervision Authority, 2024.

The decisions taken by the governments of some of the countries analysed to limit the share of foreign capital in favour of domestic capital were linked to greater involvement in this sector by state-controlled capital. This is an additional feature that differentiates the group under study. The most significant involvement of government-controlled capital is evident in Poland. The banking sector is characterised by the presence of five universal banks and one development bank, all of which are under the capital controls of the government. Collectively, these institutions hold a significant proportion of the capital in the banking sector, amounting to 48.6% (KNF, 2024).

The Hungarian government exerts ownership influence over two universal banks through indirect shareholdings. As of 31 December 2024, the Hungarian state, through Corvinus BHG Zrt., holds a significant stake of 20.01% in MBH Bank. MBH Bank was formed from the merger of Budapest Bank Takarékbank and MKB Bank, which were previously state-owned. The government-backed consolidation was intended to establish a robust domestic banking group (BNE Intellinews, 2024).

The second universal bank in which the Hungarian government has an indirect stake is OTP Bank. The Hungarian government's direct stake in the bank is negligible (0.05% as at 31 December 2024), and its influence stems mainly from the significant minority stake (8.57% as at 31 December 2024) held by the Hungarian state-controlled oil and gas company MOL.

The combined share of both banks in the assets of the Hungarian banking sector is 44.86%, and when the two Hungarian state-owned development banks, the Hungarian Export-Import Bank and the MFB Magyar Fejlesztési Bank, are also taken into account, the Hungarian

government has the ability to influence the management of 52.5% of the assets of the national banking system (Kővári, 2024).

In Romania, the state's share of capital in the banking sector was 12.2% at the beginning of 2023 (Munteanu, 2023). CEC Bank is directly dependent on the government with regard to its capital. In recent years, it has undergone significant development, rising from sixth position in terms of assets at the end of 2022 to third place within a year, overtaking Raiffeisen Bank, ING Bank and BRD-SocGen (Ernst, 2025).

The Slovak government is the proprietor of a single universal bank. The financial institution in question is Slovenská záručná a rozvoová banka, a.s. (SZRB). The primary function of the entity in question is to provide support to small and medium-sized enterprises (SMEs) and to promote the economic development of Slovakia by offering guarantees and financial services for government and EU programmes. In addition to this, the entity engages in universal banking activities, providing a comprehensive range of financial products and services. However, its impact on the broader banking sector is negligible, as its capital represents a mere 0.5% of the Slovak banking sector's capital (SZRB, 2025).

Additionally, a state-controlled bank is present in Latvia. This is the development bank Altum, which does not operate as a conventional universal bank offering a comprehensive range of retail banking services to the general public and is therefore not within the scope of this study.

In the other two countries analysed, the state does not hold any shares in any banks. The largest banking institutions in Estonia, including Swedbank, SEB Pank and Luminor, are subsidiaries of Swedish or Scandinavian financial groups. The exception to this is LHV Pank, a bank owned by Estonian proprietors and listed on the Tallinn Stock Exchange. In a similar manner, the Lithuanian banking sector is dominated mainly by Scandinavian banks. The largest universal banks, including Swedbank, SEB Bankas and Luminor, are subsidiaries of Nordic financial groups. Lithuanian capital exerts control over Šiaulių bankas, with the primary shareholders of this financial institution being private entities, namely Invalda INVL AB and UAB Willgrow.

In consideration of the aforementioned discrepancies, namely the degree of development of the banking sector, the proportion of foreign capital and the extent of state capital control, and furthermore the categorisation of a given country as either within or outside the euro area, the banking sectors of the analysed countries were divided into three groups: globalised, intermediate and nationalised. The assessment is not general in nature and only compares individual countries with the other countries included in the study. The methodology for the allocation of individual countries to groups is outlined in Table 3.

Table 3.
Degree of internationalisation of the banking sectors of CEE countries

Country	Euro	FII	Foreign capital	State capital	The nature of the sector	Points
Estonia	Yes (1)	Medium (2)	High (3)	Low (3)	Globalised	9
Hungary	No (0)	High (3)	Low (1)	High (1)	Nationalised	5
Latvia	Yes (1)	Low (1)	Medium (2)	Low (3)	Globalised	7
Lithuania	Yes (1)	Low (1)	High (3)	Low (3)	Globalised	8
Poland	No (0)	Medium (2)	Low (1)	High (1)	Nationalised	4
Romania	No (0)	Medium (2)	Medium (2)	Medium (2)	Intermediaries	6
Slovakia	Yes (1)	High (3)	High (3)	Low (3)	Globalised	10

Source: Own elaboration.

The countries that demonstrate the highest degree of openness to the influence of the global financial market in the analysed group are Slovakia and Estonia. Conversely, the countries that have granted the government and national supervisory institutions the most opportunities to influence the banking sector are Poland and Hungary.

4.2. Overview of the banking sectors in CEE countries bordering the parties to the conflict in Ukraine

The Estonian banking sector in 2019-2023

During the period under review, the Estonian banking sector consisted of 13 banks, nine of which were credit institutions licensed in the country, and four of which operated as branches of foreign credit institutions. The study encompassed eight banks licensed within the country, as detailed in Table 4, accompanied by data on the primary shareholder's nationality.

At the conclusion of 2023, the banking sector's assets totalled EUR 40 billion, constituting 106% of Estonia's GDP (EBF, 2024a). The largest market share was held by foreign banks: Swedbank, SEB Pank, and Luminor Bank, as well as the domestic LHV Pank. It is estimated that the total number of individual customers served by all banks was 2.1 million, and 0.3 million corporate customers, via 60 bank branches. The primary source of funding for banking institutions was deposits, amounting to nearly €29.5 billion. The predominant item on their assets was loans, which totalled €27.3 billion. A substantial proportion of these loans were housing loans, accounting for approximately 40% of loans extended to the non-financial sector and 80% of loans granted to households. Their share in total assets was one of the highest in the EU, indicating a potential threat to the stability of the banking sector from the real estate market.

Table 4.
Estonian universal banks included in the study

No	Bank	Main shareholder 2019-2024	Country of origin of the main shareholder
1	Bigbank	Parvel Pruunsild, Vahur Voll	Estonia
2	Coop Pank	COOP Investeeringud	Estonia
3	Inbank	Jan Andresoo	Estonia
4	LHV Pank	LHV Group	Estonia
5	Luminor Bank	Blackstone Group	United States

Cont. table 4.

6	SEB Pank	Skandinaviska Enskilda Banken	Sweden
7	Swedbank (Estonia)	Swedbank	Sweden
8	TBB Pank	Leonarda Invest AS	Estonia

Source: own study.

The International Monetary Fund (IMF) has indicated a threat to the Estonian banking sector resulting from the falling capitalisation of banks. Despite the satisfactory levels of capital remaining, these levels are in steady decline. It is noteworthy that analysts at the IMF have drawn attention to the following observation: The average capital adequacy ratio of the banking system fell from over 40% in 2014 to 21.5% in 2023. This decline can be attributed to several factors, including the growing leverage of banks and the expansion of their loan portfolios, as well as corporate tax reforms that have encouraged banks to prioritise dividend payments over retaining profits (IMF, 2024b).

Eesti Pank has expressed a divergent perspective from the IMF's evaluation, emphasising that the capitalisation ratios of the Estonian banking sector exceed the EU averages. Furthermore, it has been noted that the retained earnings at the conclusion of 2022 constituted 45% of equity, which, in turn, accounted for 10% of liabilities (Grüning et al., 2023).

Despite the considerable external shocks experienced during the period 2019-2023, including the pandemic and the outbreak of war in Ukraine, only one of the analysed banks recorded losses. TBB Bank has encountered a negative financial outcome during the 2019-2021 period. As demonstrated in Table 5, for the profitability of both equity and assets of Estonian banks, the most challenging year was undoubtedly 2020, when the pandemic broke out. It put a greater decline in asset profitability (44.74% decrease in the average ROA) and equity profitability (34.19% decrease in the average ROE). Conversely, the global uncertainty engendered by the outbreak of war in Ukraine merely decelerated the growth rate of the mean value of both profitability ratios. The war resulted in higher commodity prices, which in turn led to accelerated inflation. This, in turn, led to higher interest rates in the eurozone, which resulted in higher interest income for banks. After a period of uncertainty in 2022, they capitalised on this by achieving record levels of return on assets and equity.

Table 5.
Profitability ratios of Estonian universal banks included in the study

		ROE (%)					ROA %				
No	**Bank**	**2019**	**2020**	**2021**	**2022**	**2023**	**2019**	**2020**	**2021**	**2022**	**2023**
1	Bigbank	18.65	14.36	19.49	16.54	17.74	4.44	3.20	3.47	2.34	2.07
2	Coop Bank	7.98	7.77	12.86	15.60	23.41	1.05	0.98	1.27	1.38	2.12
3	Inbank	23.89	10.87	15.63	23.31	9.03	2.56	1.24	1.72	2.33	0.87
4	LHV Pank	14.87	17.91	25.90	24.21	30.79	0.95	0.87	1.09	1.26	2.21
5	Luminor Bank	3.15	2.01	4.65	7.96	11.58	0.37	0.23	0.53	0.89	1.29
6	SEB Bank	9.62	8.29	9.38	10.74	20.44	1.50	1.22	1.29	1.43	2.74
7	Swedbank (Estonia)	11.73	10.72	10.85	11.78	25.13	1.80	1.41	1.20	1.32	3.19
8	TBB Pank	-3.06	-14.78	-5.61	0.86	4.24	-0.44	-2.40	-0.78	0.11	0.60
	average	10.85	7.14	11.65	13.88	17.80	1.53	0.84	1.22	1.38	1.89
	dynamics of change (%)		-34.19	63.03	19.15	28.25		-44.74	44.98	12.95	36.44

Source: Own study based on Orbis data.

As with the profitability ratios, the efficiency ratios presented in Table 6 also indicate a significant negative impact in 2020 and a minor effect of uncertainty resulting from the war initiated by a neighbouring country. In 2020, the first year of the pandemic, the average C/I ratio for the analysed banks increased from 59.89% to 69.98%, indicating a decline in the sector's cost efficiency by nearly 17%. Concurrently, the net interest margin underwent a decline from 4.96% to 4.42% (-10.9%). The deterioration in efficiency in 2020 was systemic in nature and was related to a sharp increase in operating costs, growing loan loss provisions and a decline in lending activity in an environment of lower interest rates (Coop Pank, 2021; LHV Bank, 2021).

In 2021, the recovery process began, but it was uneven. The average C/I ratio decreased to 64.39%, and the margin continued to decline, reaching 3.81% (a decrease of 13.9% year-on-year). Financial institutions such as Coop Pank and LHV Pank have initiated the implementation of cost and digital strategies, thereby enhancing their operating results (Coop Pank, 2022; LHV Bank, 2022). In 2022, LHV Pank was as the most cost-effective bank, with a cost-to-income ratio of 38.58%. This was primarily driven by a growing margin of 3.47%, which was attributed to further credit expansion and a low cost base.

Notwithstanding the prevailing geopolitical turbulence in 2022, the sector demonstrated resilience, with the average C/I ratio declining to 55.06% and the margin widening to 3.96%. This was primarily attributable to the rise in interest rates within the eurozone, which resulted in an enhancement of banks' interest income. Financial institutions with a significant proportion of variable-rate loans, including LHV Pank, Coop Pank and Swedbank, exhibited an augmentation in their margins, accompanied by a subsequent diminution in C/I.

Table 6.
C/I and NIM ratios of Estonian universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Bigbank	49.91	44.94	44.47	49.90	44.75	12.19	10.53	7.89	6.72	6.14
2	Coop Bank	68.77	60.64	59.58	49.75	41.23	5.04	4.93	4.29	4.39	5.65
3	Inbank	49.93	49.71	67.29	71.20	68.06	10.29	8.78	7.18	6.40	6.03
4	LHV Pank	53.22	40.97	38.58	39.92	32.77	3.48	3.09	3.47	3.95	6.04
5	Luminor Bank	79.68	84.22	80.57	61.36	53.99	2.16	2.21	2.33	2.60	4.41
6	SEB Bank	34.50	35.80	36.01	34.03	22.57	1.99	1.82	1.72	2.19	4.23
7	Swedbank (Estonia)	38.28	40.62	41.72	42.40	24.68	2.40	2.07	1.84	2.33	4.67
8	TBB Bank	104.82	202.91	146.92	91.92	82.92	2.16	1.95	1.75	3.12	7.27
	average	59.89	69.98	64.39	55.06	46.37	4.96	4.42	3.81	3.96	5.56
	dynamics of change (%)		16.84	-7.98	-14.49	-15.78		-10.89	-13.90	4.06	40.19

Source: Own study based on Orbis data.

In 2023, efforts to enhance efficiency were further consolidated. The average C/I ratio decreased to 46.37%, representing the lowest figure observed during the period under scrutiny, while the interest margin rose to 5.56% (a 40.2% year-on-year increase). It is evident that there has been a marked improvement in the performance of commercial banks that possess a robust retail segment. This observation is exemplified by Coop Pank (C/I = 41.23%, margin = 5.65%) and LHV Pank (C/I = 32.77%, margin = 6.04%).

In summary, the pandemic exerted a short-term negative effect on the efficiency of banks, whilst the war in Ukraine had no detrimental effect on operating indicators. Estonian banks leveraged the favourable interest rate environment to enhance their cost efficiency.

The quality of Estonian banks' loan portfolios in 2019-2023, as presented in Table 7, demonstrates clear volatility, resulting from both structural trends and reactions to external shocks, including the pandemic of the Coronavirus and the invasion of Ukraine by Russia in 2022. The average share of non-performing loans fell from 3.73% in 2019 to 1.81% in 2021, a development that may be attributed to government protective measures, repayment deferrals and fiscal support, which helped to stabilise borrowers' payment situation (IMF, 2023a). In response to the enhancement in the quality of their loan portfolios, Estonian banks increased the value of loans granted in relation to deposits held in 2022, resulting in an increase of 7.38% in the L/D ratio.

However, in 2023, the NPL ratio increased once more to 2.88%, a development that can be interpreted as a consequence of both the increase in lending in the previous year and secondary economic and geopolitical tensions, including rising inflation, interest rate hikes and supply chain disruptions following the outbreak of war in Ukraine (ECB, 2023).

Table 7.
L/D and NPL ratios of Estonian universal banks included in the study

No	Bank	Loans to deposits L/D (%)					Loans at risk/Gross loans and advances to customers				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Bigbank	110.54	98.91	95.58	98.73	85.58	5.15	4.27	2.55	1.88	2.93
2	Coop Bank	90.90	88.49	86.77	86.25	86.59	1.52	1.25	0.54	0.51	0.82
3	Inbank	89.57	102.78	97.89	91.10	87.10	1.81	2.11	1.02	1.28	2.22
4	LHV Pank	61.60	47.91	44.29	62.43	64.11	0.20	0.57	0.59	0.23	0.66
5	Luminor Bank	91.14	79.46	95.08	99.00	91.24	4.14	3.59	2.18	1.22	1.90
6	SEB Bank	100.86	94.13	90.09	93.32	93.10	0.83	0.70	0.50	0.30	0.26
7	Swedbank (Estonia)	90.64	69.36	66.23	82.61	87.05	0.52	0.47	0.52	0.72	0.53
8	TBB Bank	44.47	42.84	36.47	44.19	49.29	15.64	17.29	6.54	8.63	13.71
	average	84.97	77.99	76.55	82.20	80.51	3.73	3.78	1.81	1.85	2.88
	dynamics of change (%)		-8.21	-1.84	7.38	-2.06		1.43	-52.18	2.16	55.92

Source: Own study based on Orbis data.

To summarise, the reaction of the Estonian banking sector to external stimuli with regard to the quality of loan portfolios was varied. The initial crisis impulse (Covid-19) resulted in an enhancement of portfolio quality (due to public aid and debt rollovers, amongst other factors), whilst the subsequent impulse (the outbreak of war in 2022) exposed the vulnerability of banks with weaker fundamentals. The elevated growth rate of the non-performing loan ratio in 2023 (+55.92%) across the sector can be interpreted as the result of the delayed credit risk effect (the so-called "cliff effect"), which is particularly pronounced in banks with lower capitalisation (e.g. TBB) or those experiencing rapid growth (e.g. Inbank, Bigbank).

The Latvian banking sector in 2019-2023

In 2023, the banking sector in Latvia comprised 14 institutions, including nine credit institutions that were registered in Latvia, four branches of credit institutions registered in other EU countries, and one financial holding company. Of these, a mere five were universal banks. However, it should be noted that one of these was only a subsidiary of Luminor Bank, which was already included in the Estonian banking sector study. Consequently, the final study incorporated only the four banks enumerated in Table 8.

In 2023, the volume of term deposits increased from EUR 2.6 billion to EUR 5 billion. The total value of the deposit portfolio exhibited an increase during the year from EUR 21.8 billion to EUR 22 billion. An examination of the asset side reveals a marginal increase in the total loan portfolio to EUR 15.6 billion. Of these loans, 57% were allocated to businesses, while the remaining 43% were directed towards retail customers. It is estimated that approximately one-third of loans granted to individuals were of the mortgage variety.

Table 8.
Latvian universal banks included in the study

No	Bank	Main shareholder 2019-2024	Country of origin of the main shareholder
1	Citadele Bank	Ripplewood Advisors LLC, EBOR	United States
2	Rietumu Bank Group	Leonid Esterkin, Dermot Fachtna Desmond, Arkady Suharenko	Latvia/Ireland
3	SEB Banka	SEB	Sweden
4	Swedbank (Latvia)	Swedbank	Sweden

Source: own study.

During the period under review, the Latvian banking system underwent substantial legal changes with a view to preventing money laundering. These were linked to the discovery of money laundering at ABLV Bank. In response to these challenges, the Latvian financial supervisory authority implemented a comprehensive system in 2018 aimed at preventing financial crime. This system incorporates, amongst other elements, a public-private partnership that facilitates the exchange of detailed information, encompassing not only typologies but also specific names, thereby establishing one of the most comprehensive anti-money laundering systems. In addition, Latvia has implemented a comprehensive register of beneficial owners, accompanied by rigorous verification mechanisms, and has enacted legislation prohibiting credit and payment institutions from conducting business with high-risk shell companies. This has resulted in the freezing, blocking or closure of such accounts (EBF, 2024b).

As demonstrated in the summary of ROE and ROA indicators (Table 9) for the four banks operating in Latvia analysed, it is evident that in both crisis years – 2020 and 2022 – the average returns on both equity and assets declined. The average return on equity witnessed a significant decline of 45.86% in 2020, while the return on assets experienced an even more pronounced decrease of 47.05% compared to the 2019 figures. This decline can be attributed to the repercussions of the economic crisis precipitated by the emergence of the Coronavirus

pandemic. The need for financial institutions to augment their provisions for anticipated credit losses, compounded by the diminution of interest rates within the eurozone (ECB, 2021a, 2021b), further exacerbated the situation.

The year 2021 witnessed a remarkable recovery, marked by a substantial surge in average ROE by 103.3% and ROA by 92.11%. This upturn can be attributed to several factors, including the low base level in 2020, the surge in overall economic activity following the lifting of pandemic restrictions, and the substantial decline in bank expenditure on provisions, which decreased by EUR 57.7 million, or 88.5%, across the Latvian banking sector (Latvijas Banka, 2022).

In 2022, there was a marginal decline in the average profitability of the companys, with a 2.43% decrease in ROE and a 6.95% decrease in ROA. A primary factor contributing to this correction was the outbreak of war in Ukraine, which exerted a substantial impact on the economic situation in the Baltic region. The increased economic uncertainty was manifested in a number of ways. Firstly, there was a rise in loan loss provisions. Secondly, there was a decline in lending growth. Thirdly, there was a more cautious approach by banks to expansion in markets linked to economies subject to sanctions. The war also caused disruptions in trade and logistics and inflationary pressure resulting from rising energy prices, which also meant higher operating costs for banks, limiting their ability to maintain the profit growth momentum of 2021, even despite the ongoing trend of rising interest rates (Latvijas Banka, 2023).

Table 9.
Profitability indicators for Latvian universal banks included in the study

No	Bank	ROE (%)					ROA %				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Citadele Bank	11.45	1.05	14.85	9.96	22.20	1.07	0.09	1.14	0.78	2.02
2	Rietumu Bank Group	5.68	3.59	8.41	4.96	4.67	1.41	0.74	1.91	1.18	1.17
3	SEB Banka	12.75	9.50	14.61	19.20	27.28	1.29	0.95	1.50	1.88	2.75
4	Swedbank (Latvia)	11.56	8.30	7.75	10.39	21.00	1.65	1.10	0.97	1.30	2.66
	average	10.36	5.61	11.40	11.13	18.79	1.36	0.72	1.38	1.29	2.15
	dynamics of change (%)		-45.86	103.30	-2.43	68.84		-47.05	92.11	-6.95	67.32

Source: Own study based on Orbis data.

In 2023, both ROE and ROA attained their zenith during the period under scrutiny, with an average of 18.79% and 2.15%, respectively. This phenomenon can be attributed to the repercussions of additional interest rate escalations in response to inflation and augmented interest revenue. Despite the absence of any reported losses among the Latvian banks examined in the study, notable disparities persist. Illustrative of this is the observation that SEB Banka attained the highest ROE of 27.28% in 2023, while Rietumu Bank Group maintained a substantially lower level of 4.67%. This phenomenon may be attributed to a variety of factors, including differing business models, loan portfolio structures, and levels of revenue diversification.

The cost efficiency ratio for the Latvian banks analysed exhibited significant volatility during the period under review. The mean C/I, as displayed in Table 10, increased to 66.05% in 2020 (a rise of 17.44%), which can be associated with the decrease in operating income due to the impact of the pandemic and the subsequent interest rate reductions (ECB, 2021b), whilst a considerable proportion of fixed costs remained constant. As of 2021, there was an enhancement in the cost efficiency, with the mean C/I ratio declining to 54.17% in 2022 and achieving a record low of 40.92% in 2023 (a reduction of 24.45% in comparison with 2022). This decline was attributable to various factors, including the rise in interest income in an environment of higher interest rates. This increase in interest income led to an increase in banks' revenues without a proportional increase in operating costs (EBA, 2023a).

Table 10.
C/I and NIM ratios of Latvian universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Citadele Bank	67.38	103.43	63.35	61.46	50.31	3.07	2.12	2.70	2.62	4.37
2	Rietumu Bank Group	55.71	55.42	50.71	60.53	56.94	3.18	2.99	3.13	3.28	4.71
3	SEB Bank	50.44	48.81	48.06	43.19	25.37	1.94	1.72	1.60	1.98	4.26
4	Swedbank (Latvia)	51.44	56.55	59.17	51.49	31.07	2.97	2.37	2.22	2.69	5.95
	average	56.24	66.05	55.32	54.17	40.92	2.79	2.30	2.41	2.64	4.82
	dynamics of change (%)		17.44	-16.25	-2.09	-24.45		-17.45	4.88	9.49	82.50

Source: Own study based on Orbis data.

The net interest margin in 2019-2020 underwent a substantial deterioration, with a decline from an average of 2.79% to 2.30% (representing a decrease of 17.45%). This phenomenon can be attributed to the prevailing low interest rate environment in the eurozone and the competitive pressures exerted on the credit market. From 2021 onwards, the margin exhibited a gradual increase, reaching an average of 4.82% in 2023, representing an increase of 82.5% compared to the previous year. The European Central Bank's decision to implement a series of interest rate hikes in 2022-2023 had a substantial impact on interest income, particularly for banking institutions with a substantial proportion of variable-rate loans in their portfolios.

The disparities observed between banking institutions are indicative of the substantial influence exerted by business strategies and balance sheet structures. In 2023, SEB Banka attained the lowest C/I ratio (25.37%), indicative of elevated cost efficiency and substantial digital operational scale. Conversely, Swedbank (Latvia) attained the highest interest margin in 2023, standing at 5.95%. This may be indicative of its distinct asset and liability composition, as well as its robust market position within the retail sector.

Analogous to the situation in Estonia, the pandemic of Coronavirus led to diminished efficiency in banks in Latvia. Concurrently, the war in Ukraine, with its attendant increase in energy commodity prices and consequent rise in inflation in the eurozone, resulted in an increase in interest rates that proved favourable to banks, thereby enhancing the cost efficiency of these institutions.

In the period between 2019 and 2023, the loan portfolio of Latvian banks remained relatively stable, as evidenced by the loan-to-deposit (L/D) ratios and the proportion of non-performing loans in the portfolio, as illustrated in Table 11. The mean L/D ratio for the institutions analysed fell from 63.41% in 2019 to 56.33% in 2020, a change that can be linked to a more cautious lending policy and lower demand for credit in the economy amid the uncertainty caused by the pandemic. In subsequent years, this ratio fluctuated moderately, increasing by 9.67% in 2021 as businesses and consumers returned to normal operations, falling by 2.35% in the following year of uncertainty caused by the war in Ukraine, and finally reaching 63.93% in 2023 after an increase of 5.99%, suggesting a return of Latvian banks to their pre-pandemic lending activity.

Table 11.
L/D and NPL ratios of Latvian universal banks included in the study

No	Bank	Loans to deposits L/D (%)					Loans at risk / Gross loans and advances to customers				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Citadele Bank	47.79	37.40	62.93	65.99	73.82	4.80	3.48	3.27	2.69	2.29
2	Rietumu Bank Group	44.25	52.01	51.96	54.93	58.58	30.91	27.29	24.64	28.74	24.68
3	SEB Bank	88.62	81.87	74.86	65.16	67.68					
4	Swedbank (Latvia)	72.98	54.06	57.38	55.20	55.65	0.98	1.39	1.00	0.41	0.40
	average	63.41	56.33	61.78	60.32	63.93	12.23	10.72	9.64	10.61	9.12
	dynamics of change (%)		-11.16	9.67	-2.36	5.99		-12.37	-10.09	10.14	-14.04

Source: Own study based on Orbis data.

Concurrently, there was a downward trend in the share of non-performing loans in the portfolio – from 12.23% in 2019 to 9.12% in 2023. This improvement is indicative of an enhancement in the quality of banks' assets, notwithstanding the considerable challenges experienced, including supply chain disruptions and geopolitical tensions that have arisen in the wake of the Ukraine war in 2022. The war has increased credit risk in the region, but the Latvian banking sector has demonstrated relative resilience, partly due to conservative lending standards and high capital reserves (ECB, 2023).

The Lithuanian banking sector in 2019-2023

As of the conclusion of 2023, the Lithuanian banking sector comprised a total of 13 domestic banks and 6 branches of foreign credit institutions. The period was distinguished by a high degree of concentration, with the three largest banks holding 70% of the system's assets at the conclusion of 2022, representing a decline from 84% in 2018. (IMF, 2023b). In the context of this study, seven banking institutions were engaged in universal banking activities. However, only four of these institutions, as detailed in Table 12, were selected for inclusion in the study. Omitted: Luminor Bank was previously delineated in the section on Estonia, Citadele Bank, was in the section on Latvia, and Revolut Bank does not conform to the conventional banking model but rather operates as a fintech entity, having commenced its operations at the culmination of 2019 and swiftly ascending to become the third largest banking

institution in Lithuania, holding an 18% share of the system's assets, but 98% of its deposits were sourced from non-Lithuania residents (IMF, 2023b).

Table 12.
Lithuanian universal banks included in the study

No	Bank	Main shareholder 2019-2024	Country of origin of the main shareholder
1	Medicinos Bankas	Konstantinas Karosas	Lithuania
2	SEB Bank	Scandinavian Enskilda Bank	Sweden
3	Šiaulių Bankas	Invalda INVL	Lithuania
4	Swedbank (Lithuania)	Swedbank	Sweden

Source: own study.

The economic consequences of the 2020-2021 pandemic were marked by a decline in economic activity, a slowdown in lending, and increased market uncertainty. In 2020, 11 banks and branches of foreign banks concluded the year with a profit, while 5 banks incurred losses. The latter group was dominated by entities undergoing restructuring, starting or ending their operations (Bank of Lithuania, 2021). Concurrently, the pandemic precipitated the acceleration of the digitisation of services (Pu et al., 2021) and increase in the importance of the fintech sector, which has been undergoing dynamic development in Lithuania since the mid-2010s.

The outbreak of war in Ukraine in 2022 triggered a series of economic consequences, including inflationary pressure, interest rate hikes, and increased energy and import costs. The European Central Bank initiated a cycle of aggressive interest rate hikes, which, in the case of Lithuania (as well as Estonia and Latvia), with a dominant share of variable-rate loans, resulted in a significant increase in banks' interest income. This has been demonstrated to result in enhanced profitability ratios and to increase the cost of loan servicing for households and businesses (Bank of Lithuania, 2023b). Consequently, banking institutions are obligated to allocate a greater proportion of their assets to reserves for credit risk.

Notwithstanding the economic turbulence, Lithuania's banking sector demonstrated resilience in maintaining adequate capital and liquidity levels. The elevated cost efficiency and advanced digital infrastructure of financial institutions have been identified as key factors in their resilience. The proliferation of fintech entities has also been shown to generate novel opportunities for the diversification of services (Bitinas, Burkšaitiene, 2024).

In the period between 2019 and 2023, the profitability of Lithuanian banks, as measured by the return on equity (ROE) and return on assets (ROA) ratios, was subject to significant fluctuations. These fluctuations were attributable to macroeconomic, regulatory and geopolitical factors. The data presented in Table 13 indicate that the pandemic had a negative impact on the profitability of Lithuanian banks, while the outbreak of war had a positive impact. The average ROE exhibited a decline from 14.68% in 2019 to 11.32% in 2020, representing a 22.83% decrease. This decline can be attributed to the direct impact of the pandemic, the restriction of lending, and the persistent low interest rates (ECB, 2021b). Following a negligible alteration in profitability in 2021, a discernible enhancement in return on equity was evident from 2022 onwards, reaching 21.89% in 2023. This phenomenon can be attributed

to a precipitous rise in interest rates, a recovery in credit demand, and an augmentation in net interest income (Bank of Lithuania, 2023a). A comparable trend was observed in the case of ROA, which, after a decline in 2019-2021 (from 1.48% to 1.08%), rose to 1.92% in 2023.

Table 13.
Profitability ratios of Lithuanian universal banks included in the study

No	Bank	ROE (%)					ROA %				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Medicinos Bankas	11.86	10.58	10.87	12.03	16.62	1.13	1.03	1.10	1.33	1.82
2	SEB Bankas	15.10	11.21	12.50	17.51	26.96	1.43	0.99	1.07	1.40	2.20
3	Šiaulių Bankas	17.60	12.93	14.50	15.88	15.29	2.16	1.55	1.58	1.66	1.68
4	Swedbank (Lithuania)	14.14	10.58	8.67	13.47	28.67	1.19	0.79	0.57	0.83	1.99
	average	14.68	11.32	11.63	14.72	21.89	1.48	1.09	1.08	1.31	1.92
	dynamics of change (%)		-22.83	2.74	26.54	48.65		-26.21	-1.13	20.89	47.32

Source: Own study based on Orbis data.

A further factor that stimulated profitability growth in 2022–2023 was the outbreak of war in Ukraine. Despite the initial increase in risk, this led to increased activity by banks in the area of corporate financing, particularly in sectors related to logistics, energy and security (ECB, 2023). The increase in Lithuania's nominal GDP and inflation during this period led to a rise in banks' interest and commission income (Bank of Lithuania, 2023a).

The cost efficiency ratios of Lithuanian banks from 2019 to 2023, as presented in Table 14, exhibited discernible variations between institutions. The average C/I ratio decreased from 48.02% in 2019 to 43.84% in 2023, suggesting enhanced productivity and optimised resource utilisation. However, this decline commenced with the onset of the war in Ukraine, which may imply the significance of higher interest rates in this enhancement. The most significant decline in C/I was observed at Medicinos Bankas, where there was an improvement from 71.78% to 62.22%. This can be attributed to the implementation of digitisation and operational optimisation processes (Bank of Lithuania, 2023a; Klapper, Miller, 2021).

The enhancement in cost efficiency across the sector in 2022-2023 coincided with a substantial increase in the interest margin – from 2.94% to 4.96% – as a consequence of dynamic interest rate hikes in the eurozone since mid-2022. The most significant increases in interest margins were observed among banking institutions with substantial retail deposit bases, such as Swedbank and SEB Bankas. These institutions were able to substantially boost their interest income, a feat facilitated by the favourable financing costs (IMF, 2023b).

Table 14.
C/I and NIM ratios of Lithuanian universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Medicinos Bankas	71.78	68.46	69.37	68.42	62.22	3.47	3.84	4.01	4.25	6.26
2	SEB Bankas	34.89	38.20	38.01	32.10	32.78	1.85	1.51	1.46	1.97	4.41
3	Šiaulių Bankas	39.14	40.13	41.62	40.27	39.93	3.23	3.10	2.91	3.08	3.68
4	Swedbank (Lithuania)	46.29	49.56	54.44	42.41	40.42	2.34	1.92	1.58	2.47	5.47
	average	48.02	49.09	50.86	45.80	43.84	2.72	2.59	2.49	2.94	4.96
	dynamics of change (%)		2.22	3.61	-9.95	-4.28		-4.77	-3.85	18.10	68.39

Source: Own study based on Orbis data.

The average L/D ratio in Lithuanian banks decreased from 73.12% in 2019 to 57.80% in 2021 (Table 15). This decline can be attributed to a more cautious lending environment and an increase in the deposit base amidst prevailing economic uncertainty (ECB, 2021b). This decline was consistent with the trend observed across the euro area, where households and businesses accumulated liquidity in the face of falling consumption and investment.

Table 15.
L/D and NPL ratios of Lithuanian universal banks included in the study

No	Bank	Loans to deposits L/D (%)					Loans at risk / Gross loans and advances to customers				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Medicinos Bankas	66.45	59.92	61.28	74.45	68.49	3.38	3.51	2.62	1.69	2.88
2	SEB Bankas	82.80	63.00	63.04	54.98	56.38	1.80	1.76	1.08	0.86	0.39
3	Šiaulių Bankas	80.40	69.06	62.81	76.46	79.08	5.31	6.86	3.44	2.79	2.86
4	Swedbank (Lithuania)	62.82	49.11	44.06	47.96	55.80	1.22	1.11	0.64	0.49	0.52
	average	73.12	60.27	57.80	63.46	64.94	2.93	3.31	1.95	1.46	1.66
	dynamics of change (%)		-17.57	-4.10	9.80	2.32		13.08	-41.20	-25.10	14.07

Source: Own study based on Orbis data.

The L/D ratio increased from 2022 onwards, achieving an average of 64.94% in 2023. This recovery can be linked to the economic upturn after the pandemic and growing demand for financing in conditions of high inflation and accelerated implementation of investment projects, particularly in the renewable energy sector, supported by EU funds (Bank of Lithuania, 2023a).

Concurrently, there was a substantial decrease in the proportion of non-performing loans, from 2.93% in 2019 to 1.46% in 2022. This decline can be attributed, at least in part, to the protective measures implemented by the government and the central bank, including loan moratoriums and guarantee programmes (Bank of Lithuania, 2021). In 2023, this ratio increased to 1.66%, which may be indicative of the initial manifestations of a decline in the quality of the loan portfolio amidst an economic slowdown and elevated interest rates consequent to the European Central Bank's (ECB) policy of monetary tightening following the eruption of the Ukraine war.

The Polish banking sector in 2019-2023

As indicated by the National Bank of Poland (NBP), the ratio of Polish banks' assets to Gross Domestic Product (GDP) was 87.8% in 2023, representing a decline from 97.1% in 2021. This figure was notably lower than in other countries in the region, including the Czech Republic (129.9%) and Hungary (100.6%), and lower than the eurozone average of 269.8% (NBP, 2024). Statistics from the Central Statistical Office indicate that at the end of 2023, the banking sector's balance sheet total reached PLN 2,994.8 billion, and the net result was PLN 27.6 billion (GUS, 2024). In terms of the structure of entities, at the end of 2023 there were 29 commercial banks, 492 cooperative banks and 34 branches of credit institutions operating (EBF, 2024c). The study encompassed 18 banking institutions engaged in universal

activities – 16 commercial banks and 2 cooperative banks with nationwide coverage – as detailed in Table 16.

The proportion of assets held by foreign-owned entities decreased from 46.8% to 43.1% between 2018 and 2022 (BIS, 2024). In 2023, eight commercial banks controlled by Polish capital (including those with State Treasury participation) held a total of 56.4% of the sector's assets, confirming the dominant role of domestic ownership and the government's significant influence on the banking sector (EBF, 2024c). Simultaneously, the extant literature suggests that the ownership status of banks in Poland (state vs. private/foreign) differentiates their cost efficiency and risk models. Periods of financial turbulence, such as the global pandemic and the war in Ukraine, have highlighted different propensities to lend and shock transmission mechanisms (Goniszewski, 2024).

Three phenomena had a significant impact on the results of Polish banks: firstly, the emergence of the Coronavirus pandemic and the subsequent regulatory and tax shields (interest rate cuts in 2020, protective programmes); secondly, mass challenges in courts to mortgage agreements denominated in foreign currencies; and thirdly, a cycle of interest rate hikes in 2021-2022. The NBP has published documentation which indicates that following the decline in profitability precipitated by the pandemic, the banks experienced an improvement in financial performance during the 2022-2023 period. This recovery was attributed to an increase in interest margins and a substantial deposit base. However, the NBP also noted that the results were adversely affected by credit holidays and legal provisions for the foreign currency loan portfolio (NBP, 2024). Research undertaken in both industry and academia has demonstrated that the materialisation of legal risk on foreign currency loans has become a primary factor exerting pressure on the profits of selected banks. The scale of write-offs and provisions could reach tens of billions of PLN (Fitch Ratings, 2023). In turn, the war in Ukraine – through the influx of refugees, increased transaction activity and deposits, and strong uncertainty – changed the structure of financing and demand for selected products, but did not affect liquidity stability (NBP, 2023).

Table 16.
Polish universal banks included in the study

No	Bank	Main shareholder 2019-2024	Country of origin of the main shareholder
1	Alior Bank	PZU	Poland
2	Bank BPS	ZBS	Poland
3	Handlowy Bank	Citibank OIC	United States of America
4	Millennium Bank	BCP	Portugal
5	Bank for Environmental Protection	NFOSiGW	Poland
6	Postal Bank	Polish Post Office	Poland
7	Bank of Poland	PZU, PFR	Poland
8	BNP Parisbas Bank Polska	BNP Paribas	France
9	Credit Agricole Bank Polska	Credit Agricole	France
10	Deutsche Bank Poland	Deutsche Bank	Germany
11	ING Bank Silesian	ING Bank	Netherlands

Cont. table 16.

12	mBank	Commerzbank	Germany
13	Nest Bank	Porto Group Holdings Limited	Great Britain
14	PKO Bank Polski	Ministry of Finance	Poland
15	Plus Bank	Zygmunt Solorz (through the Cypriot company Karswell)	Poland
16	Santander Bank Polska	Banco Santander	Spain
17	Santander Consumer Bank	Banco Santander	Spain
18	SGB Bank	Cooperative banks	Poland

Source: own study.

From the perspective of efficiency and financing structure, in 2023 the NBP recorded a persistent shortage of long-term market financing and a significant mismatch in interest rate maturities, although these did not constitute a source of systemic risk given the dispersed deposit base (NBP, 2023). Research on the factors influencing bank profitability within the European Union indicates that in a group of countries exhibiting a profile analogous to that of Poland, the most significant factors pertain to macroeconomic factors (inflation, interest rate cycle), asset quality (cost of risk) and financing structure (Bernardelli et al., 2024). Moreover, the extant literature on the genesis of controlling capital demonstrates that Polish banks in which the State Treasury held ownership rights exhibited a divergent response to the shocks experienced between 2020 and 2022 in terms of efficiency, profitability and lending when compared with private banks (Goniszewski, 2024). As posited by Klepczarek et al. (2024), analogous disparities were evident among financial institutions in Poland, classified as either domestic or foreign-owned, with respect to cost efficiency.

Table 17.
Profitability ratios of Polish universal banks included in the study

		ROE					ROA %				
No	**Bank**	**2019**	**2020**	**2021**	**2022**	**2023**	**2019**	**2020**	**2021**	**2022**	**2023**
1	Alior Bank	3.76	-4.68	7.72	11.30	26.33	0.33	-0.40	0.60	0.82	2.35
2	BPS Bank	-5.73	0.72	4.86	-4.38	9.07	-0.21	0.02	0.16	-0.15	0.27
3	Handlowy Bank	6.80	2.35	9.59	20.15	25.51	0.95	0.31	1.17	2.35	3.15
4	Bank Millennium	6.47	0.25	-16.87	-16.64	9.29	0.63	0.02	-1.32	-0.94	0.49
5	Bank Ochrony Środowiska	3.32	-14.92	2.51	6.70	3.81	0.39	-1.57	0.23	0.61	0.36
6	Postal Bank	3.12	-1.47	5.98	25.58	36.32	0.24	-0.11	0.34	1.19	2.55
7	Bank of Poland	9.38	4.51	8.82	7.37	24.78	1.10	0.51	0.90	0.65	2.24
8	BNP Paribas Bank Polska	5.66	6.32	1.51	3.90	8.39	0.56	0.64	0.14	0.31	0.65
9	Credit Agricole Bank Polska	2.35	-4.80	1.25	1.56	4.18	0.29	-0.54	0.12	0.13	0.39
10	Deutsche Bank Poland	0.25	-15.22	-27.06	-32.12	-52.87	0.03	-1.83	-2.62	-2.19	-3.26
11	ING Bank Silesia	11.62	7.91	14.36	14.99	34.04	1.10	0.77	1.19	0.82	1.92
12	mBank	6.45	0.63	-7.76	-5.32	0.18	0.66	0.06	-0.62	-0.34	0.01
13	Nest Bank	-29.78	-22.67	0.37	8.15	1.03	-2.81	-2.01	0.03	0.74	0.09
14	PKO Bank Polski	10.00	-6.29	12.56	9.02	13.60	1.20	-0.71	1.23	0.78	1.18
15	Plus Bank	-54.70	-152.71	-116.08	88.99	34.60	-0.35	-2.16	-0.94	4.62	4.63
16	Santander Bank Polska	9.12	4.45	4.48	10.81	15.92	1.17	0.56	0.53	1.20	1.85
17	Santander Consumer Bank	15.65	8.39	4.50	9.68	1.69	2.60	1.46	0.89	2.07	0.36
18	SGB Bank	3.63	0.98	1.66	2.63	2.62	0.12	0.03	0.05	0.09	0.09

Cont. table 17.

	average	0.41	-10.35	-4.87	9.02	11.03	0.44	-0.28	0.12	0.71	1.07
	dynamics of change (%)		-2627.14	52.97	285.35	22.25		-161.88	142.02	513.46	51.41

Source: Own study based on Orbis data.

In contrast to the situation in banks in the Baltic states, where only one bank recorded a loss in the analysed period, Polish banks encountered significant challenges in achieving profitability, as illustrated in Table 17. The average return on equity in the sector fell from 0.41% in 2019 to (-10.35%) in 2020, reflecting the impact of the pandemic, interest rate cuts and increased risk costs. The average return on equity remained in the negative throughout 2021, only turning positive in 2022 when it reached 9.02%, and continuing to improve to 11.03% in 2023. The average return on assets also fell to a negative value (-0.28%) in 2020, but was positive from 2021 onwards, finally reaching 1.07% in 2023.

In 2020, the principal factor contributing to the decline in results was the decision of the Monetary Policy Council to reduce interest rates. This decision resulted in a decrease in banks' interest income (NBP, 2021). Concurrently, the pandemic compelled the establishment of supplementary credit risk provisions, which exerted a deleterious effect on the sector's outcomes (Boda, 2022), and a substantial source of pressure emerged in the form of mounting legal risk costs associated with foreign currency loans, which subsequently resulted in the accumulation of multi-billion reserves in subsequent years (Polkowska, 2024).

The enhancement in profitability since 2021 can be attributed to the recovery of economic activity and the escalation in interest rates during the 2021-2022 period, which resulted in an augmentation in net interest income. The data demonstrate that a significant proportion of banking institutions recorded double-digit ROE during this period, including Bank Handlowy (25.5% in 2023), ING Bank Ślaski (34.0%) and Bank Pocztowy (36.3%). Nevertheless, there were still significant differences between entities – while the largest universal banks achieved stable positive profitability, Deutsche Bank Polska remained permanently in deficit, and some smaller banks (e.g. Plus Bank) were characterised by extreme volatility in their results.

As indicated by scientific analyses, the diversity of bank profitability in Poland was influenced: ownership structure and links to foreign capital, and credit portfolio quality and cost efficiency (Klepczarek et al., 2024). Bernadelli, Korzeba and Niedziółka's (2024) study highlighted that, within the Polish context, macroeconomic variables (e.g. inflation, interest rates) exerted a pivotal influence on profitability. However, sectoral variables, encompassing the financing structure and the cost of risk, were also found to be significant. In contrast, Goniszewski (2024) has observed that state-owned and private banks demonstrated divergent responses to the shocks posed by the pandemic and the war in Ukraine. Specifically, state-owned banks exhibited reduced flexibility but concomitant enhanced stability with respect to lending.

The average cost-to-income ratio, as presented in Table 18, underwent deterioration in 2020, reaching 77.7% in comparison to 63.8% in 2019. This can be attributed to a decrease in interest income, resulting from interest rates falling to unprecedentedly low levels. The deterioration in cost efficiency was particularly evident in banks with a relatively weak capital position and high exposure to risk costs, such as Deutsche Bank Polska and Plus Bank, whose C/I ratio exceeded 120% in 2020 and remained high in subsequent years.

However, a marked improvement in efficiency was observed in 2021-2023, as evidenced by a decline in the average C/I ratio to 61.9% in 2023. This decline signifies an enhanced capacity on the part of banks to generate income in the face of rising interest rates and an ameliorating economic climate. However, the results of individual banks exhibited significant variation - for instance, the state-owned Alior Bank, the cooperative Bank BPS, and the foreign Bank Handlowy exhibited enhanced efficiency. Conversely, other institutions experienced an escalation in their cost-to-income ratio in 2023 compared to 2019. For instance, one may cite the cooperative SGB Bank, the state-owned PKO BP, and the foreign Nest Bank.

Analogous tendencies were observable in the interest margin. The average level decreased from 3.63% in 2019 to 2.77% in 2021, a consequence of the pandemic and record low interest rates. However, following the commencement of the cycle of interest rate hikes in the fourth quarter of 2021, the margin underwent dynamic growth, reaching 4.62% in 2023. The most favourable conditions for improving the interest margin were recorded by retail banks with a large share of consumer loans in their portfolios, such as Alior Bank (5.81% in 2023), Bank Pocztowy (5.91%) and Plus Bank (7.46%). Conversely, cooperative banks maintained a low interest margin, typically around 1%.

Table 18.
C/I and NIM ratios of Polish universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Alior Bank	53.25	59.67	52.51	54.13	41.96	4.49	3.88	3.68	4.57	5.81
2	BPS Bank	87.87	82.11	76.35	98.88	71.63	1.35	1.22	1.04	1.01	1.24
3	Handlowy Bank	59.71	65.94	56.73	42.57	36.35	2.69	2.00	1.47	4.57	4.79
4	Bank Millennium	58.42	60.60	57.32	61.39	33.75	2.86	2.76	2.83	3.40	4.87
5	Bank Ochrony Środowiska	64.99	119.18	70.32	69.86	80.91	2.39	2.00	1.94	3.81	3.93
6	Postal Bank	70.32	75.49	76.58	67.51	48.73	3.63	2.83	2.44	5.01	5.91
7	Bank of Poland	55.74	58.05	56.43	55.97	41.36	3.00	2.51	2.45	3.30	4.36
8	BNP Paribas Bank Polska	71.74	63.21	61.85	66.36	50.13	3.09	2.86	2.66	2.61	3.55
9	Credit Agricole Bank Polska	72.56	80.89	75.30	75.51	77.47	5.31	4.37	3.80	4.27	5.27
10	Deutsche Bank Poland	88.25	184.91	268.74	158.10	201.97	1.01	0.92	0.64	2.39	3.23
11	ING Bank Silesia	50.83	52.32	51.12	55.73	40.95	2.92	2.68	2.61	2.75	3.66
12	mBank	59.98	51.84	51.83	53.27	37.03	2.86	2.52	2.35	3.23	4.79
13	Nest Bank	51.58	55.61	57.30	53.32	62.93	9.11	7.34	6.49	7.59	7.25
14	PKO Bank Polski	52.68	94.11	49.22	64.37	59.83	3.37	3.06	2.64	2.89	4.22
15	Plus Bank	91.12	125.90	102.34	81.35	68.33	4.73	3.17	2.79	6.43	7.46

Cont. table 18.

16	Santander Bank Polska	50.43	52.86	49.19	58.23	51.12	3.41	2.86	2.68	4.12	5.23
17	Santander Consumer Bank	43.76	48.03	40.66	37.89	37.42	7.95	6.47	6.29	7.17	6.46
18	SGB Bank	64.76	67.67	73.23	74.41	73.64	1.21	1.14	1.02	1.05	1.09
	average	63.78	77.69	73.72	68.27	61.97	3.63	3.03	2.77	3.90	4.62
	dynamics of change (%)		21.81	-5.10	-7.40	-9.22		-16.50	-8.74	40.85	18.46

Source: Own study based on Orbis data.

The extant literature highlights three principal factors that exerted influence on fluctuations in interest margins and the efficiency of Polish banks during the period under scrutiny: (1) monetary policy and the dynamic shifts in interest rates; (2) legal regulations and the associated risks pertinent to the foreign currency loan portfolio, compelling the establishment of additional reserves (Polkowska, 2024); and (3) digital transformation, which, in the long term, contributed to enhanced cost efficiency (Kasiewicz et al., 2022).

Table 19.
L/D and NPL ratios of Polish universal banks included in the study

		Loans to deposits L/D (%)					**Loans at risk / Gross loans and advances to customers**				
No	**Bank**	**2019**	**2020**	**2021**	**2022**	**2023**	**2019**	**2020**	**2021**	**2022**	**2023**
1	Alior Bank	85.05	83.08	80.36	81.22	80.94	14.53	14.51	11.83	9.86	8.63
2	BPS Bank	36.31	31.25	34.61	27.77	21.86	13.19	12.63	12.12	12.69	12.52
3	Handlowy Bank	52.34	41.57	41.92	36.87	32.32	3.72	3.94	4.38	4.20	4.19
4	Bank Millennium	84.33	88.92	85.74	77.60	68.31	4.47	4.85	4.30	4.39	4.54
5	Bank Ochrony Środowiska	77.39	68.74	65.98	58.67	57.76	15.21	15.64	13.45	14.82	13.45
6	Postal Bank	72.03	59.69	54.22	51.69	47.14	9.78	11.06	10.81	11.37	8.99
7	Bank of Poland	87.55	78.26	80.02	72.21	68.38	5.55	5.72	5.41	6.73	6.75
8	BNP Paribas Bank Polska	84.90	81.44	83.18	73.06	66.89	5.75	5.42	3.68	3.28	3.01
9	Credit Agricole Bank Polska	83.11	75.38	74.14	74.54	78.20	7.36				
10	Deutsche Bank Poland	63.92	60.01	59.73	33.51	39.63	3.37	5.01	6.17	4.93	6.30
11	ING Bank Silesia	88.82	79.51	82.55	80.10	75.64	2.92	3.24	2.54	2.26	2.64
12	mBank	89.25	78.60	73.21	67.54	60.25	4.01	4.44	3.79	3.89	4.16
13	Nest Bank	83.12	75.20	66.46	55.80	44.45	17.41	19.77	20.39	25.28	27.68
14	PKO Bank Polski	89.25	78.11	71.84	68.14	61.04	4.10	4.26	3.84	3.68	3.49
15	Plus Bank	69.87	55.71	44.06	51.57	46.69	54.62	62.93	68.59	73.30	79.52
16	Santander Bank Poland	90.03	81.03	79.15	75.84	75.13	5.12	5.69	4.91	4.86	4.53
17	Santander Consumer Bank	112.56	110.94	104.19	103.70	96.42	9.51	11.36	11.12	10.33	8.14
18	SGB Bank	20.12	18.59	17.24	17.02	15.02					
	average	76.11	69.22	66.59	61.49	57.56	10.62	11.90	11.71	12.24	12.41
	dynamics of change (%)		-9.05	-3.81	-7.65	-6.39		12.04	-1.65	4.56	1.36

Source: Own calculations based on Orbis data.

The average loan-to-deposit ratio (see Table 19) exhibited a decline from 76.1% in 2019 to 57.6% in 2023. The impetus for this change can be traced back to two primary factors. Firstly, in 2020-2021, households and businesses accumulated excess liquidity (fiscal transfers, deferred consumption, uncertainty), which increased the deposit base at a faster rate than lending, while record low interest rates prompted banks to reduce lending in favour of safer investments in treasury securities (NBP, 2021). In subsequent years, following the initiation of the interest rate hiking cycle in Q4 2021, there was a decline in demand for credit, particularly for housing, while deposits remained at elevated levels, further reducing the L/D ratio (NBP, 2021). The ratio exhibited the most significant decline at prominent banking institutions with substantial mortgage portfolios. For instance, mBank witnessed a decline from 89.3% (2019) to 60.3% (2023), while PKO BP experienced a decrease from 89.3% to 61.0%, and Bank Millennium from 84.3% to 68.3%. Concurrently, financial institutions specialising in consumer lending maintained higher L/D ratios, as evidenced by Santander Consumer Bank's transition from an L/D ratio of 112.6% to 96.4%, indicative of their business model characterised by a substantial proportion of retail loans financed by retail deposits (NBP, 2023).

The average proportion of items classified as non-performing loans increased from 10.6% in 2019 to 12.4% in 2023. However, this ratio varied significantly between banks. In the 2020-2021 period, loan moratoriums and public guarantee programmes delayed the recognition of credit losses, resulting in a moderate deterioration in asset quality indicators despite the severe pandemic shock (NBP, 2021). Following the expiration of the financial instruments known as "shields" and increase in the cost of money during the 2022-2023 period, the part of loans portfolios transitioned to higher risk categories. However, the magnitude of losses remained constrained, largely due to the robust financial position of banking institutions and their substantial capital reserves (NBP, 2023). The tabular data illustrate the heterogeneity: Alior experienced a decline in its ratio from 14.5% to 8.6%, a development attributable to the streamlining of its retail portfolio. Conversely, Nest Bank demonstrated an increase in its ratio from 17.4% to 27.7%, a growth that can be attributed to its increased exposure to segments that exhibit greater sensitivity to the economic cycle. Plus Bank (54.6% → 79.5%) serves as an extreme case in point, confirming that portfolio concentration and institutional risk can may outweigh macro factors.

The Slovak banking sector in 2019-2023

The Slovak banking system is characterised by a high degree of concentration, with the majority of its assets being under foreign control. A review conducted by the European Commission has revealed that the five largest banking institutions collectively possessed approximately 79% of the sector's assets in 2022. This finding indicates that Slovakia has a higher level of asset concentration compared to the EU average. Concurrently, the financial soundness and asset quality indicators demonstrated stability, with the LCR reaching 152% in Q3 2022 and the proportion of non-performing loans declining to approximately 1.8%, marking

the lowest level since 2016. (EC, 2023). The study encompassed the results of eight banking institutions listed in Table 20. Among them is Slovenska Zarucna a Rozvojova Banka, which is a development bank but also conducts universal banking activities.

The years 2020-2021 witnessed a period of substantial growth in mortgage sales and property prices, coinciding with a period of extremely low interest rates in the aftermath of the global pandemic Covid-19. In December 2021, the European Systemic Risk Board (ESRB) issued a warning to Slovakia, highlighting the "medium-term vulnerabilities" of the housing market, which included price revaluation and rapid growth in household debt (ESRB, 2021). Concurrently, the NBS reinforced its macroprudential framework, maintaining, among other provisions, LTV/DTI limits and identifying the risk of switching from fixed interest rates to higher rates when interest rates are subject to change (NBS, 2022).

Table 20.
Slovak universal banks included in the study

No	Bank	Main shareholder 2019-2024	Country of origin of the main shareholder
1	365.Bank	J&T Finance Group	Slovakia
2	Ceskoslovenska Obchodna Banka	KBC Group	Belgium
3	Prima Banka Slovensko	Penta Investments	Slovakia
4	Privatbanka	Penta Investments	Slovakia
5	Slovenska Sporitel'na	Erste Bank	Austria
6	Slovak Guarantee and Development Bank	Ministry of Finance	Slovakia
7	Tatra Bank	Raiffeisen Bank International	Austria
8	Vseobecna Uverova Banka	Intesa Sanpaolo	Italy

Source: own study.

In the aftermath of Russia's incursion into Ukraine and the subsequent surge in inflation in 2022, there was a precipitous rise in interest rates within the eurozone, which rapidly translated into increased mortgage costs in Slovakia. In accordance with the observations recorded by the NBS, the median rate for new mortgages exhibited an increase from approximately 1.0% to around 3.8% during the course of 2022. This development is believed to have exerted a restrictive influence on demand for new debt, thereby contributing to a moderation in housing activity. Simultaneously, the central bank concluded that the rise in instalments remained "manageable" for the majority of households. This assessment was concurred with by the IMF, which calculated a low percentage of households susceptible to insolvency in the event of interest rate fluctuations (NBS, 2022b).

A political risk that emerged towards the end of 2023 was the discussion on the introduction of a special bank tax, which, according to economists, could reduce the ability of banks to absorb shocks and finance the economy (S&P Global, 2023). Overall, however, the sector remained resilient, while the need to continue monitoring exposure to the housing market and structural concentration remained (IMF, 2025).

The empirical data presented in Table 21 demonstrate that the average return on equity underwent a significant decline from 7.8% in 2019 to 5.36% in 2020, representing a substantial decrease of more than 31%. A similar trend was observed in the return on assets, which fell from 0.92% in 2019 to 0.61% in 2020. The primary factors contributing to this decline were the adverse effects of the pandemic, including the freeze on certain economic activities, the European Central Bank's interest rate reductions, and the implementation of moratorium on loan repayments, which led to a reduction in banks' interest income (Clichici, Zeldea, 2021).

Since 2021, there has been an improvement in the results, with the average ROE rising to 7.81% and the ROA to 0.88%. However, this process has been uneven among banking institutions. The most substantial growth was observed among prominent universal institutions, including Slovenská Sporiteľňa and Tatra Banka, which profited from the escalating credit dynamics within the economy and the systematic withdrawal of aid programmes (NBS, 2022a). Conversely, smaller banks, such as Prima Banka Slovensko, exhibited lower and more stable, albeit less dynamic, profitability.

Table 21.
Profitability ratios of Slovak universal banks included in the study

No	Bank	ROE					ROA %				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	365.Bank	5.90	6.13	8.00	12.27	11.20	0.87	0.91	1.21	1.90	1.73
2	Ceskoslovenska Obchodna Banka	8.18	5.05	8.29	6.92	8.44	0.71	0.44	0.71	0.53	0.65
3	Prima Banka Slovensko	5.07	4.93	4.82	5.10	11.35	0.44	0.40	0.37	0.35	0.79
4	Privatbanka	10.29	6.34	10.03	11.80	17.45	1.22	0.83	1.49	1.73	2.44
5	Slovenska Sporitel'na	11.49	6.33	11.87	11.48	13.30	1.00	0.55	1.04	1.04	1.23
6	Slovak Guarantee and Development Bank	2.67	0.96	1.19	1.56	3.80	1.42	0.58	0.74	0.99	2.26
7	Tatra Banka	11.38	8.17	11.67	12.80	15.27	0.98	0.70	0.92	0.91	1.08
8	Vseobecna Uverova Banka	7.44	4.98	6.59	9.42	13.14	0.70	0.45	0.53	0.74	1.12
	average	7.80	5.36	7.81	8.92	11.74	0.92	0.61	0.88	1.02	1.41
	dynamics of change (%)		-31.29	45.59	14.25	31.67		-33.77	44.25	16.83	37.97

Source: Own study based on Orbis data.

The year 2022 witnessed a further strengthening of indicators – average ROE was 8.92% and ROA was 1.02%. This increase was primarily attributable to the initiation of a cycle of interest rate hikes in the euro area, which resulted in an augmentation of banks' interest income. A further factor that contributed to the enhancement of financial results was the augmentation in lending, notably in the mortgage segment. Nevertheless, apprehensions concerning the quality of the loan portfolio were concurrently expressed, due to rising inflation and the war in Ukraine.

In 2023, the sector attained its most profitable position during the period under review, with average returns on equity (ROE) reaching 11.74% and returns on assets (ROA) at 1.41%. The most significant enhancements were observed at banking institutions such as Privatbanka (ROE 17.45%) and Tatra Banka (ROE 15.27%). As posited by the NBS report (NBS, 2023b),

the observed growth can be attributed to a propitious interest rate environment and the sector's robust capital position.

The average C/I ratio increased in 2020 (63.55% vs. 61.22% in 2019) and then gradually declined to 50.44% in 2023 (a decrease of 13.11 percentage points compared to 2020). As demonstrated in Table 22, the most substantial decline in C/I was observed among universal and large-scale banking institutions, namely Slovenská Sporiteľňa, Tatra Banka and VÚB. This phenomenon can be attributed to the recovery of interest income and the implementation of cost discipline following the implementation of pandemic support programmes.

Table 22.
C/I and NIM ratios of Slovak universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	365.Bank	59.84	56.48	57.95	56.01	57.57	4.46	3.95	3.62	3.27	3.60
2	Ceskoslovenska Obchodna Banka	68.34	67.80	74.75	67.42	69.45	2.12	2.01	1.87	1.76	1.73
3	Prima Banka Slovensko	72.89	73.75	70.31	70.17	57.28	1.69	1.40	1.11	0.95	1.19
4	Privatbanka	48.69	61.52	55.10	51.71	41.36	2.13	2.06	2.05	2.19	3.71
5	Slovenska Sporitel'na	55.61	57.67	52.36	50.42	45.65	2.50	2.38	2.22	2.12	2.32
6	Slovak Guarantee and Development Bank	64.17	74.76	62.03	61.79	44.09	2.20	2.46	2.64	2.57	5.54
7	Tatra Banka	60.36	54.77	50.88	48.98	46.10	2.37	2.19	2.09	2.02	2.34
8	Vseobecna Uverova Banka	59.84	61.64	55.71	50.34	41.99	2.20	1.76	1.53	1.69	2.61
	average	61.22	63.55	59.89	57.11	50.44	2.46	2.28	2.14	2.07	2.88
	dynamics of change (%)		3.81	-5.77	-4.64	-11.68		-7.45	-5.97	-3.27	39.05

Source: Own study based on Orbis data.

The average interest margin underwent a decline from 2.46% in 2019 to 2.07% in 2022, followed by a substantial increase to 2.88% in 2023, representing a 39% year-on-year growth. The mechanism is consistent with the typical behaviour of eurozone banks: the cycle of ECB rate hikes since July 2022 has resulted in increased interest income at a rate that has outpaced financing costs (particularly those from household deposits). The EBA identifies this as the primary source of interest income growth. Concurrently, during the latter half of 2023, initial indications of stabilisation and a decline in credit demand emerged, which has the potential to constrain further expansion in the margin (EBA, 2023b).

An analysis of the data presented in Table 23 indicates that between 2019 and 2023, the banking sector in Slovakia exhibited a relatively stable L/D ratio (103–106%), concurrently accompanied by a substantial decline in the proportion of non-performing loans in portfolios (from 4.37% in 2019 to 3.75% in 2023). However, it should be noted that this trend varies between banking institutions. Prima Banka and ČSOB exhibited an increase in the degree of transformation of deposits into loans (L/D above 120% in 2022–2023), while Privatbanka and SZRB demonstrated an unstable financing profile, characterised by elevated (SZRB: 170-208%) or diminished (Privatbanka: ~50-60%) L/D values.

The ratio of non-performing loans in the period under review demonstrated a consistent downward trend in most commercial banks (e.g. Slovenská Sporiteľňa – from 3.05% in 2019 to 2.38% in 2023; Tatra Banka – from 2.05% to 1.63%). The exceptions to this were observed in the fluctuations at Privatbanka (rise to 12.4% in 2020, falling to 4.9% in 2023) and SZRB, where the ratio rose to 11.6% in 2022 and then fell slightly (10.4% in 2023). These figures reflect the sensitivity of the loan portfolios of institutions with a specialised business profile, which are more dependent on sectoral and cyclical risks.

Table 23.
L/D and NPL ratios of Slovak universal banks included in the study

No	Bank	Loans to deposits L/D (%)					Loans at risk / Gross loans and advances to customers				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	365.Bank	67.21	75.81	78.77	78.62	76.52	7.76	7.05	6.11	5.84	6.47
2	Ceskoslovenska Obchodna Banka	117.25	105.70	122.67	122.71	119.91	1.85	1.96	1.73	1.17	1.48
3	Prima Banka Slovensko	105.04	106.18	113.24	120.95	131.91	3.02	2.33	1.68	0.97	0.86
4	Privatbanka	59.04	52.67	47.31	62.95	50.92	5.10	12.42	11.98	7.58	4.90
5	Slovenska Sporitel'na	95.57	89.39	83.58	98.27	99.55	3.05	2.50	2.21	2.07	2.38
6	Slovak Guarantee and Development Bank	194.34	195.84	208.61	170.93	145.33	9.06	7.70	8.99	11.59	10.37
7	Tatra Banka	91.50	92.28	92.47	88.96	89.98	2.05	2.02	1.89	1.66	1.63
8	Vseobecna Uverova Banka	115.73	115.26	88.87	109.24	109.99	3.10	2.67	2.41	1.86	1.87
	average	105.71	104.14	104.44	106.58	103.01	4.37	4.83	4.62	4.09	3.75
	dynamics of change (%)		-1.48	0.29	2.05	-3.34		10.52	-4.30	-11.51	-8.49

Source: Own study based on Orbis data.

From a macroeconomic perspective, the enhancement in asset quality during the 2021-2023 period was underpinned by a swift economic recovery following the pandemic, minimal unemployment and robust real wage growth, thereby augmenting borrowers' capacity to meet their obligations (IMF, 2022). Concurrently, loan moratoriums and guarantee programmes in 2020-2021 led to a substantial curtailment in the short-term growth of non-performing loans, thereby effectuating a temporal shift in risk (NBS, 2021).

The Hungarian banking sector in 2019-2023

The study of the Hungarian universal banking sector includes the nine banks presented in Table 24, although the Magyar Nemzeti Bank (MNB) considers eight banks to be universal in its analyses. The Bank of China is a bank whose universal activities may be subject to debate. It focuses on corporate banking, but also offers deposit and loan products for individual customers. It is therefore included in this study.

In the initial phase of the pandemic, there was a decline in bank profitability in Hungary due to a slowdown in economic activity, historically low interest rates and a widespread credit moratorium. Research based on MNB transaction data demonstrates that the moratorium

curtailed the short-term escalation in insolvency, yet concomitantly exerted pressure on interest income and precipitated a shift in risk over time (Drabancz et al., 2021; Aczél et al., 2023).

Table 24.
Hungarian universal banks included in the study

No	Bank	Main shareholder 2019–2024	Country of origin of the main shareholder
1	Bank of China	Bank of China	China
2	CIB Bank	Intesa Sanpaolo	Italy
3	Erste Bank Hungary	Erste Group Bank	Austria
4	Granit Bank	TiberisDigital	Hungary
5	K&H Bank	KBC Group	Belgium
6	MBH Bank	Zenith Asset Management, Corvinus BHG	Hungary
7	OTP Bank	distributed shareholding, including MOL	Hungary
8	Raiffeisen Bank	Raiffeisen Bank	Austria
9	Unicredit Bank Hungary	Unicredit Bank	Italy

Source: own study.

In 2021, with the thawing of the economy, the MNB credit programmes and the gradual withdrawal of shields, there was a rebound in lending, particularly in the field of mortgages. In 2022, the inflation shock (following, inter alia, Russia's aggression against Ukraine) prompted the MNB to tighten financial conditions significantly, while the government introduced protective instruments (including interest rate caps) and additional sectoral levies. The MNB's financial stability reports indicate that the combination of high inflation, rising interest rates and protective regulations led to a limitation of new mortgage lending. However, this did not compromise the stability of asset quality or bank liquidity (MNB, 2023).

The year 2023 witnessed a substantial enhancement in results, primarily attributable to a notable broadening of interest margins in the context of elevated interest rates and a decelerated pass-through to deposit costs. The EBA identifies the increase in NIM as the primary factor contributing to the enhancement in the profitability of EU banks in 2023, a phenomenon that is also evident in the data pertaining to Hungary. Concurrently, lending activity experienced a downturn, and financing costs began to escalate. According to the MNB and the EBA, this may potentially compromise the viability of margins in forthcoming years (EBA, 2023a; MNB, 2023).

From a macroprudential perspective, the MNB assesses the sector as being resistant in terms of capital and liquidity, with low levels of non-performing loans and limited transition of moratoriums into permanent losses. Concurrently, the IMF observes that the substantial financial gains of banking institutions in 2023 were accomplished notwithstanding the implementation of discretionary sectoral taxes and additional government interventions, underscoring the considerable influence of interest rates and margins on the sector's effectiveness. Further risks have been identified by the MNB and the IMF, including a slowdown in lending, financing costs, household sensitivity to interest rate changes, and regulatory and tax uncertainty (IMF, 2024a).

In 2020, the impact of the pandemic and the introduction of a credit moratorium resulted in a substantial decline in bank profitability. The mean return on equity (ROE) fell from 12.69% in 2019 to 6.84% in 2020, and the mean return on assets (ROA) fell from 1.34% to 0.63% (see Table 25).

Table 25.
Profitability ratios of Hungarian universal banks included in the study

No	Bank	ROE (%)					ROA %				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Bank of China	1.34	4.71	-0.26	19.66	27.90	0.12	0.36	-0.02	1.18	1.52
2	CIB Bank	5.67	3.02	6.16	13.37	21.50	0.68	0.33	0.61	1.23	1.99
3	Erste Bank Hungary	15.90	5.56	13.50	11.87	22.76	2.19	0.69	1.49	1.14	2.32
4	Granit Bank	8.03	8.88	16.52	27.60	31.15	0.30	0.32	0.62	1.36	1.82
5	K&H Bank	15.30	11.08	17.93	15.65	21.81	1.51	1.07	1.57	1.25	1.95
6	MBH Bank	24.76	4.13	26.11	17.23	20.00	2.44	0.37	1.97	1.31	1.69
7	OTP Bank	20.04	10.75	16.38	10.92	26.71	2.38	1.19	1.79	1.15	2.74
8	Raiffeisen Bank	9.22	5.32	13.96	22.73	25.26	0.83	0.45	1.05	1.77	2.36
9	Unicredit Bank Hungary	13.89	8.09	11.88	21.57	21.14	1.59	0.84	1.07	1.76	1.81
	average	12.69	6.84	13.57	17.84	24.25	1.34	0.63	1.13	1.35	2.02
	dynamics of change (%)		-46.09	98.49	31.46	35.88		-53.30	80.43	19.69	49.79

Source: Own study based on Orbis data.

In 2021, a recovery was observed, with the thawing of the economy and stabilisation measures implemented by the Hungarian National Bank contributing to an enhancement in lending and a reduction in loss provisions. The average return on equity (ROE) increased almost twofold, reaching 13.57%, while the return on assets (ROA) rose to 1.13%. MBH Bank demonstrated the highest profitability during this period (ROE 26.11%). However, the financial performance of banks was adversely impacted by the imposition of tax obligations and interest rate caps by the Hungarian government. These measures, implemented to regulate economic policies, constrained the extent to which favourable macroeconomic conditions could be capitalised upon by the banks.

The period of 2022-2023 witnessed a marked acceleration in profit growth. In 2022, the average return on equity (ROE) was 17.84%, and in 2023 it increased to a record 24.25%. Analogous trends were observed in ROA (from 1.35% to 2.02%). This phenomenon was attributable to the MNB tightening its monetary policy in response to high inflation and the weakening of the forint. The combination of elevated interest rates and the delayed transmission of these rates to deposit costs resulted in a substantial augmentation of the interest margin and a remarkable enhancement in banks' performance.

Concurrently, profits were constrained by the imposition of supplementary fiscal obligations on the banking sector by the government, which, as stated in the IMF (2024), persisted as a primary source of risk to the sector's stability. Nevertheless, 2023 witnessed

remarkably elevated profits, particularly for the most substantial institutions – OTP Bank recorded an escalation in ROE to 26.71% and Granit Bank to 31.15%.

Table 26.
C/I and NIM ratios of Hungarian universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Bank of China	92.65	87.75	95.74	71.03	56.93	0.61	0.97	0.24	2.14	2.71
2	CIB Bank	78.48	76.07	67.73	54.34	51.07	1.42	1.55	2.19	5.01	5.81
3	Erste Bank Hungary	59.21	62.00	58.91	66.57	53.23	2.90	2.74	2.86	4.12	3.67
4	Granit Bank	79.74	76.05	63.15	51.21	47.32	0.85	1.07	1.45	3.04	4.39
5	K&H Bank	64.00	58.86	58.18	66.88	60.30	2.76	2.54	2.39	3.54	4.68
6	MBH Bank	63.47	82.12	59.43	67.61	59.56	2.42	1.47	2.26	6.44	6.12
7	OTP Bank	56.78	59.90	60.18	63.47	49.14	4.75	4.23	3.98	4.26	4.89
8	Raiffeisen Bank	81.44	76.46	64.83	58.40	56.85	1.76	1.92	2.14	4.08	5.76
9	Unicredit Bank Hungary	52.52	55.46	57.42	50.45	56.09	2.10	2.13	2.37	3.90	3.80
	average	69.81	70.52	65.06	61.11	54.50	2.17	2.07	2.21	4.06	4.65
	dynamics of change (%)		1.01	-7.73	-6.08	-10.81		-4.87	6.83	83.66	14.51

Source: Own study based on Orbis data.

The mean cost to income ratio in the examined group of Hungarian banks, as displayed in Table 26, diminished from 69.81% in 2019 to 54.50% in 2023, denoting a discernible enhancement in cost efficiency. This was primarily attributable to the escalating interest income that materialised as a consequence of the cycle of interest rate hikes implemented by the MNB in 2021-2022. Banks such as OTP Bank and MBH Bank reduced their C/I ratios to below 60%, while the Bank of China, which had the highest costs in 2019 (92.65%), improved its efficiency to 56.93% in 2023.

The average interest margin for the sector increased from 2.17% in 2019 to 4.65% in 2023. The most significant enhancements were observed at CIB Bank (from 1.42% to 5.81%) and MBH Bank (from 2.42% to 6.12%). The increase in margins was closely related to dynamic interest rate hikes in Hungary (the main reference rate rose from 0.6% in 2020 to 13% in 2022), which increased banks' interest income, particularly in the corporate and mortgage loan segments (MNB, 2023).

Concurrently, OTP Bank, as the largest universal bank in the country, maintained a stable interest margin (4.75% in 2019 and 4.89% in 2023), indicating the relative resilience of its business model to changes in macroeconomic conditions.

The mean L/D ratio of the Hungarian banks included in the study, as presented in Table 27, exhibited a decline from 59.09% in 2019 to 52.71% in 2023, with the lowest values being recorded in 2021 (47.25%). This decline indicates limited lending growth relative to deposit growth, which was primarily the result of economic uncertainty caused by the pandemic and an increase in the propensity of households and businesses to save (ECB, 2021b).

Table 27.
L/D and NPL ratios of Hungarian universal banks included in the study

No	Bank	Loans to deposits L/D (%)					Loans at risk / Gross loans and advances to customers				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Bank of China	26.99	29.29	18.89	37.52	20.15					
2	CIB Bank	60.15	56.23	50.83	53.68	53.84	4.36	4.29	3.94	3.82	2.25
3	Erste Bank Hungary	69.23	59.14	52.92	56.00	62.52	3.58	4.04	4.26	3.13	2.82
4	Granit Bank	44.52	35.60	34.69	31.04	28.65					
5	K&H Bank	55.50	50.74	45.87	52.10	57.88	3.24	2.22	2.59	2.25	1.96
6	MBH Bank	75.61	59.55	53.46	69.52	69.31	4.68	3.08	3.27	4.15	3.33
7	OTP Bank	74.32	70.48	69.31	69.38	67.00	6.26	5.99	5.42	5.11	4.29
8	Raiffeisen Bank	56.70	53.21	45.67	53.42	50.51	4.96	3.73	4.77	3.62	3.12
9	Unicredit Bank Hungary	68.74	56.24	53.66	62.00	64.52	1.32	3.12	2.80	2.41	2.13
	average	59.09	52.28	47.25	53.85	52.71	4.06	3.78	3.86	3.50	2.84
	dynamics of change (%)		-11.52	-9.61	13.96	-2.12		-6.75	2.14	-9.47	-18.74

Source: Own study based on Orbis data.

Universal banks, including OTP Bank and MBH Bank, exhibited a relatively elevated L/D ratio (approximately 67-70% in 2023), attributable to their proactive financing of investment projects and expansion within the Central and Eastern European region (Gadeev, Deuber, 2023a,b,c). Conversely, the Bank of China maintained remarkably low loan-to-deposit ratios (20.15% in 2023), indicative of its distinct business model, which prioritises corporate services and cross-border transactions over the domestic retail sector.

The proportion of non-performing loans decreased on average in the analysed group from 4.06% in 2019 to 2.84% in 2023, indicating a discernible enhancement in the quality of the loan portfolio. The most significant decline was observed at OTP Bank (from 6.26% in 2019 to 4.29% in 2023). This change was a consequence of two factors. Firstly, there was an improvement in the quality of the loan portfolio. Secondly, there were active sales and restructuring of non-performing loans. The bank reported this information in its annual reports (OTP Bank, 2023, 2024).

The Romanian banking sector in 2019-2023

The Romanian banking sector exhibits a low level of financial intermediation in comparison to the EU. The ratio of bank credit to the private sector to GDP remained among the lowest in the Union throughout the period under review. Concurrently, the ratios of capital, liquidity, and asset quality remained within acceptable limits, and the sector demonstrated notable resilience to external shocks, including the pandemic, inflation, and the war in Ukraine. At the conclusion of 2022, the National Bank of Romania (BNR) evaluated the sector's overall prudential posture as stable, notwithstanding the deterioration in the macro-financial environment. In 2023, Romanian banks demonstrated adequate capital, maintained liquidity

and profitability, although real credit growth turned negative as a result of monetary policy tightening and high inflation (BNR, 2023a, IMF, 2023c).

Table 28.
Romanian universal banks included in the study

No	Bank	Main shareholder 2019-2024	Country of origin of the main shareholder
1	Alpha Bank Romania	UniCredit	Italy
2	Intesa Sanpaolo Commercial Bank Romania	Intesa Sanpaolo	Italy
3	Romanian Commercial Bank	Erste Group	Austria
4	BRD-Groupe Societe Generale	Societe Generale	France
5	CEC Bank	Ministry of Finance	Romania
6	Credit Europe Bank	Husnu Mustafa Ozyegin	Turkey
7	First Bank	JC Flowers & Co.	United States of America
8	Garanti Bank	Banco Bilbao Vizcaya Argentaria	Spain
9	Libra Internet Bank	NCH Balkan Fund, L.P	United States of America
10	OTP Bank Romania	OTP Bank Group	Hungary
11	Procredit Bank	Procredit Holding	Germany
12	Raiffeisen Bank	Raiffeisen Bank International	Austria
13	Salt Bank	Getin Holding/Banca Transilvania	Poland/Romania
14	Transilvania Bank	distributed shareholding	Romania
15	Unicredit Bank	Unicredit	Italy

Source: own study.

The Romanian banking sector, despite the inclusion of 15 universal banks (listed in Table 28) and three more not included, is concentrated: the largest banks (including Banca Transilvania, BCR, BRD, Raiffeisen, UniCredit, CEC) control most of the assets, and consolidation continued in 2022–2023 (among others, EximBank merged with Banca Românească and on 10 May 2023 adopted the brand name Exim Banca Românească, formally transitioning to a universal bank model). In December 2023, the NBR indicated that the announced transactions would further consolidate the market (Exim Bank, 2022, NBR, 2023c).

The mean return on equity of the analysed group of Romanian banks fell to 4.3% in 2020, which represented a 58% decline compared to 2019, while in subsequent years a clear recovery was observed: to 9.83% in 2021, 11.17% in 2022 and 12.63% in 2023, as shown in Table 29. The return on assets (ROA) demonstrated a comparable trend, declining to 0.47% in 2020 and reaching 1.32% in 2023. The data therefore indicate a significant improvement in the sector's profitability in the post-pandemic period, supported by high interest rates and an increase in the interest margin (BNR, 2023c).

Table 29.
Profitability ratios of Romanian universal banks included in the study

No	Bank	ROE (%)					ROA %				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Alpha Bank Romania	4.40	4.05	5.39	6.24	8.40	0.45	0.43	0.58	0.65	0.83
2	Banca Comercială Intesa Sanpaolo Romania	6.84	0.92	1.49	3.38	4.15	0.92	0.12	0.19	0.42	0.54
3	Banca Comercială Română	7.05	9.14	14.79	16.81	19.73	0.81	1.04	1.64	1.85	2.24
4	BRD-Groupe Société Générale	18.93	10.72	13.42	15.88	20.93	2.64	1.59	1.99	1.87	2.10
5	CEC Bank	12.57	8.00	8.17	11.09	11.83	1.27	0.91	0.82	0.75	0.71
6	Credit Europe Bank	7.15	-2.29	8.13	3.46	7.46	1.39	-0.47	1.66	0.74	1.81
7	First Bank	14.52	-9.00	7.36	7.06	6.48	1.56	-0.95	0.80	0.79	0.71
8	Garanti Bank	8.18	5.03	8.27	12.26	10.07	1.05	0.70	1.18	1.61	1.24
9	Libra Internet Bank	17.19	5.09	21.68	24.47	27.56	1.92	0.55	2.14	2.47	3.04
10	OTP Bank Romania	4.98	0.15	-0.51	3.29	10.76	0.58	0.02	-0.06	0.36	1.23
11	Procredit Bank	-8.03	-11.10	4.13	6.21	7.91	-1.00	-1.19	0.37	0.53	0.68
12	Raiffeisen Bank	18.52	12.32	15.08	21.28	24.15	1.97	1.33	1.46	2.05	2.55
13	Salt Bank	8.02	7.92	7.79	-3.16	-13.54	0.61	0.63	0.65	-0.29	-1.90
14	Transilvania Bank	21.62	14.51	19.30	24.84	25.54	2.18	1.43	1.69	1.82	1.93
15	Unicredit Bank	12.63	9.09	13.01	14.48	17.95	1.28	0.97	1.49	1.63	2.04
	average	10.30	4.30	9.83	11.17	12.63	1.18	0.47	1.11	1.15	1.32
	dynamics of change (%)		-58.23	128.50	13.62	13.00		-59.73	133.67	3.92	14.49

Source: Own elaboration based on Orbis data.

The ongoing Coronavirus pandemic had a distinctly deleterious effect on the financial health of banking institutions in Romania, most notably in 2020, when losses were incurred by several institutions (for instance, First Bank and ProCredit Bank). Empirical research has confirmed that the pandemic pressure reduced banks' financial results, limiting interest income growth and increasing risk costs, although loan moratoriums mitigated the immediate increase in the share of non-performing loans (Dinu, Bunea, 2022; Vierescu, 2023).

Since 2021, there has been a marked improvement in profitability, with major banking institutions such as Banca Comercială Românească, BRD-Groupe Société Générale, Raiffeisen Bank and Banca Transilvania attaining double-digit returns on equity and returns on assets. The highest ratios in 2022-2023 were recorded by Libra Internet Bank (ROE 27.56% in 2023) and Banca Transilvania (ROE 25.54%), indicating the ability of some institutions to adapt more quickly to market conditions. A common factor was the improvement in net interest income amid restrictive monetary policy – the NBR's main rate was raised from 1.25% in 2021 to 7% in 2023 (NBR, 2023b).

Table 30.
C/I and NIM ratios of Romanian universal banks included in the study

No	Bank	Cost efficiency C/I (%)					Interest margin (%)				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Alpha Bank Romania	80.50	75.02	77.42	75.00	70.93	3.34	3.25	3.10	3.37	3.76
2	Banca Comercială Intesa Sanpaolo Romania	80.85	74.23	86.94	70.00	73.40	3.19	2.74	2.71	3.30	3.33
3	Romanian Commercial Bank	77.77	57.88	51.54	46.24	43.58	3.73	3.59	3.39	3.76	4.14
4	BRD-Groupe Société Générale	51.19	51.16	52.00	50.41	49.83	4.42	4.02	3.60	3.81	4.10
5	CEC Bank	64.68	52.99	56.09	54.00	50.60	4.74			4.86	5.83
6	Credit Europe Bank	74.66	68.61	63.91	73.51	76.67	4.57	4.73	4.32	4.44	5.67
7	First Bank	81.89	111.04	90.57	82.29	84.55	3.83	3.73	3.57	4.05	4.35
8	Garanti Bank	75.15	64.98	64.00	55.71	71.46	3.27	3.34	3.34	3.13	3.14
9	Libra Internet Bank	56.78	56.68	50.17	46.71	41.93	5.50	4.76	4.80	5.70	6.54
10	OTP Bank Romania	68.15	72.56	81.32	68.96	63.25	3.92	3.72	3.33	3.77	4.67
11	Procredit Bank	130.57	121.10	84.14	70.43	73.80	3.27	3.30	3.21	3.85	4.37
12	Raiffeisen Bank	53.95	57.21	54.37	50.52	47.09	5.11	4.61	4.12	4.80	5.20
13	Salt Bank	75.05	72.34	72.85	81.80	79.80	4.08	3.70	3.67	3.07	3.19
14	Transilvania Bank	48.70	46.05	49.13	48.77	46.04	4.42	3.81	3.25	3.82	4.04
15	Unicredit Bank	46.60	42.70	47.00	43.91	37.80	3.48	3.37	3.34	3.64	4.16
	average	71.10	68.30	65.43	61.22	60.72	4.06	3.76	3.55	3.96	4.43
	dynamics of change (%)		-3.93	-4.20	-6.44	-0.82		-7.26	-5.59	11.40	11.99

Source: Own study based on Orbis data.

The cost efficiency of Romanian banks, measured by the cost-to-income ratio, exhibited a marked enhancement between 2019 and 2023. The mean C/I ratio in the aforementioned group decreased from 71.1% in 2019 to 60.7% in 2023, representing a reduction of approximately 15% over a five-year period (see Table 30). Banca Comercială Românească (a decrease from 77.77% to 43.58%) and Unicredit Bank (from 46.60% to 37.80%) demonstrated particularly significant enhancements in efficiency. The highest C/I ratios were maintained by smaller and specialised banks, such as ProCredit Bank and First Bank, which struggled with high operating costs in 2019-2021 (BNR, 2023c).

Concurrently with the enhancement in operating efficiency, the net interest margin underwent an increase. The average for the entire sector increased from 4.06% in 2019 to 4.43% in 2023, with the strongest increases recorded at Libra Internet Bank (from 5.50% to 6.54%) and CEC Bank (from 4.74% to 5.83%). The increase in margins was attributable to the NBR's implementation of interest rate hikes, which resulted in augmented interest income (NBR, 2021, 2023b).

Table 31.
L/D and NPL ratios of Romanian universal banks included in the study

No	Bank	Loans to deposits L/D (%)					Loans at risk / Gross loans and advances to customers				
		2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
1	Alpha Bank Romania	84.93	84.10	85.01	85.08	84.26	6.16	4.99	4.45	2.61	2.56
2	Banca Comercială Intesa Sanpaolo Romania	82.71	85.53	85.25	70.71	67.51	6.74	6.53	5.89	5.58	3.76
3	Romanian Commercial Bank	67.09	64.36	64.78	70.67	71.99	4.37	4.82	4.17	3.01	3.07
4	BRD-Groupe Société Générale	66.53	60.36	64.46	62.42	66.49	4.19	4.08	3.76	3.12	2.62
14	CEC Bank	60.88	55.88	54.24	51.34	41.12	5.04	5.52	5.29	4.41	4.14
5	Credit Europe Bank	67.52	61.86	61.57	74.43	67.70	12.04	9.63	7.77	5.79	7.26
6	First Bank	68.11	63.73	69.13	71.75	65.05	5.36	6.27	6.14	4.36	4.46
7	Garanti Bank	79.94	83.68	83.82	83.22	77.32	4.02	3.62	2.71	2.13	1.97
8	Libra Internet Bank	70.81	72.34	65.22	72.71	69.43	2.27	2.18	1.94	1.61	2.11
9	OTP Bank Romania	107.64	105.31	96.26	100.10	90.87	6.19	5.04	4.66	4.71	5.44
10	Procredit Bank	88.39	105.85	98.57	86.48	87.49	2.22	1.74	1.64	1.56	1.36
11	Raiffeisen Bank	76.71	66.36	66.30	80.31	76.37	4.81	4.36	3.82	2.87	2.83
12	Salt Bank	85.50	82.25	80.19	81.97	93.06	6.46	4.59	4.83	5.49	13.76
13	Transilvania Bank	51.93	45.31	48.44	55.19	54.19	7.19	6.36	4.54	3.79	3.57
15	Unicredit Bank	69.46	79.04	81.81	79.03	77.60	7.06	7.34	5.86	3.64	3.14
	average	75.21	74.40	73.67	75.03	72.70	5.61	5.14	4.50	3.65	4.14
	dynamics of change (%)		-1.08	-0.98	1.84	-3.11		-8.37	-12.45	-18.96	13.48

Source: Own study based on Orbis data.

The extant literature indicates that the increase in the interest margin in Romania was also the result of a shift in loan portfolios towards the household and SME segments, which are characterised by higher interest rates than large corporations (Ichim et al., 2022). Moreover, in an environment characterised by high inflation (with figures exceeding 13% in the 2022-2023 period), financial institutions effectively transposed a proportion of their expenses to borrowers, thereby fortifying their interest income (IMF, 2023c).

An analysis of the L/D ratio and the share of non-performing loans indicates stabilisation and an overall strengthening of the loan portfolio of banks in Romania in 2019-2023. The mean L/D ratio in the aforementioned group (see Table 31) demonstrated stability and remained below the EU level, suggesting a prudent approach to the utilisation of deposits for loan financing (EBF, 2024d).

Concurrently, there has been a substantial enhancement in the quality of the loan portfolio. The average share of non-performing loans fell from 5.6% in 2019 to 3.7% in 2022, with a slight increase in 2023 to around 4.1%. This trend is indicative of the efficacy of banking institutions' restructuring measures, the enhancement in the quality of loans granted, and the ongoing rectification of balance sheets following a period of elevated non-performing loans (NPLs). As demonstrated by BNR and EBF data, the NPL ratio in Romania in 2023 was a mere 2.4%, thus classifying the banking system as one of the most robust in the EU (EC, 2024).

4.3. Comparison of banking sectors in CEE countries bordering participants in the conflict in Ukraine

Profitability

In Table 32, the average profitability ratios of universal banks in the individual countries analysed are summarised. In addition to the above-described cases, the table also includes averages for the Czech Republic and Bulgaria. These were included in order to check whether the outbreak of war in Ukraine had a different impact on the banking systems of countries bordering the participants in the conflict than on countries that do not border them. In the Czech Republic, higher return on equity values can be observed than in other countries throughout the entire period analysed, except for the last year, when profitability increased across the entire group analysed. The average return on equity in Bulgaria is comparable to that observed in other countries. With respect to the dynamics of change in profitability in 2022, when the war in Ukraine broke out, neither the Czech Republic nor Bulgaria are distinguished from the other countries. With regard to the return on assets and its dynamics, there is no significant distinction between the Czech Republic and Bulgaria and the other countries. The findings of this study do not permit the conclusion that proximity to participants in the Ukraine conflict is a variable that affects the profitability of the banking sector.

In the period under review, Poland was the country with the lowest profitability of the universal banking sector. It was the only country to record a deficit instead of return on equity in 2020 and 2021, and on assets in 2020, in the average result achieved by banks. The Polish banking sector's lack of resilience to the negative impact of the pandemic is also evident in the dynamics of change that took place between 2019 and 2020. This decline represents a substantial decrease in the average return on equity, with a magnitude of 2627%. In comparison, other countries experienced a more modest decline, ranging from a few dozen percent to a maximum of 58% in Romania and 46.09% in Hungary. In 2020, Poland also exhibited the most unfavourable result with regard to the dynamics of the decline in return on assets, registering a figure of -161.88%. By contrast, in other countries, the decline did not exceed 60% - the highest rate recorded was in Romania (-59.73%) and Hungary (-53.30%). A comparison of these results with the breakdown of the analysed group of countries in Table 32 reveals that the banking sectors of countries whose nature was described as nationalised and indirect exhibited the most negative reaction to the outbreak of the pandemic in terms of profitability.

Table 32.
Average values of profitability indicators and their dynamics in universal banking sectors in CEE countries

Country	ROE (%)					ROA %				
	2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
average										
Estonia	10.85	7.14	11.65	13.88	17.80	1.53	0.84	1.22	1.38	1.89
Hungary	12.69	6.84	13.57	17.84	24.25	1.34	0.63	1.13	1.35	2.02
Latvia	10.36	5.61	11.40	11.13	18.79	1.36	0.72	1.38	1.29	2.15
Lithuania	14.68	11.32	11.63	14.72	21.89	1.48	1.09	1.08	1.31	1.92
Poland	0.41	-10.35	-4.87	9.02	11.03	0.44	-0.28	0.12	0.71	1.07
Romania	10.30	4.30	9.83	11.17	12.63	1.18	0.47	1.11	1.15	1.32
Slovakia	7.80	5.36	7.81	8.92	11.74	0.92	0.61	0.88	1.02	1.41
Bulgaria	9.59	5.92	7.67	10.60	17.09	1.28	0.78	1.03	1.24	1.82
Czech Republic	19.16	8.96	17.08	18.82	18.28	1.32	0.67	1.07	1.34	1.36
dynamics of change (%)										
Estonia		-34.19	63.03	19.15	28.25		-44.74	44.98	12.95	36.44
Hungary		-46.09	98.49	31.46	35.88		-53.30	80.43	19.69	49.79
Latvia		-45.86	103.30	-2.43	68.84		-47.05	92.11	-6.95	67.32
Lithuania		-22.83	2.74	26.54	48.65		-26.21	-1.13	20.89	47.32
Poland		-2627.14	52.97	285.35	22.25		-161.88	142.02	513.46	51.41
Romania		-58.23	128.50	13.62	13.00		-59.73	133.67	3.92	14.49
Slovakia		-31.29	45.59	14.25	31.67		-33.77	44.25	16.83	37.97
Bulgaria		-38.24	29.60	38.13	61.21		-38.91	31.22	20.44	47.45
Czech Republic		-53.26	90.68	10.22	-2.88		-48.95	58.72	25.84	0.98

Source: Own study based on Orbis data.

The countries where the average return on equity of universal banks exhibited the least decline in response to the pandemic were Lithuania (-22.83%), Slovakia (-31.29%), and Estonia (-34.19%). Furthermore, these same countries also recorded the smallest decline in return on assets. These are countries whose banking sectors have been described as the most globalised.

The outbreak of war in Ukraine did not have as clear an impact on the profitability of the analysed group of banks as the pandemic. A decline in return on equity was recorded by only one country, namely Latvia, in 2022. This decline was recorded as -2.43%. A similar decline was recorded in return on assets, which was -6.95%. An examination of the financial data reveals that other countries have experienced an uptick in profitability. This phenomenon can be attributed to the mechanism outlined in the respective national sector descriptions. The war has been identified as a contributing factor to the escalation in raw material prices, which subsequently led to elevated levels of inflation. This, in turn, prompted central banks to implement an increase in interest rates, thereby augmenting banks' interest-related income. The lowest increases in return on equity were recorded in Romania (13.62%) and Slovakia (14.25%). The highest increases were in Poland (285.35%) and Hungary (31.46%). The lowest increases in asset profitability were recorded in Romania (3.92%) and Estonia (12.95%), while the highest were in Poland (513.46%) and Hungary (19.69%).

Comparing the dynamics of changes in profitability in the year the war broke out in Ukraine with the breakdown in Table 32, it can be seen that globalised or indirect banking sectors reacted negatively or least positively to the war, while nationalised sectors reacted most positively.

In summary, it can be posited that the pandemic exerted the most deleterious effect on the profitability of banking sectors in Central and Eastern Europe where the state exerted the greatest influence on the banking sector, while the outbreak of war in the same countries engendered the most marked increases in profitability. This may lead to the conclusion that in this region of Europe, greater political influence on the banking sector leads to greater volatility in bank profitability.

Efficiency

In Table 33, the average efficiency ratios of universal banks in each of the countries analysed are summarised. In order to verify the hypothesis that geographical proximity to military conflict has a stronger negative impact on the banking sector, two countries that are not directly adjacent to the parties to the conflict were included in the summary.

In the year the war broke out, all the countries analysed saw an improvement in their cost efficiency ratio, suggesting that the proximity of war did not exert a negative impact on the efficiency of the banking sector. The most significant decline in the indicator, i.e. enhancement in efficiency, was evident in the Czech Republic (-18.11%), which may imply that the distance from the conflict exerts a favourable influence, though this is not substantiated by the outcome observed in the Bulgarian banking sector, where the enhancement in efficiency is average in comparison to other nations.

With regard to the average interest margin and its alteration in the year the war broke out, the results achieved by the two more distant countries are indistinguishable from those achieved by the countries adjacent to the participants in the conflict. In consideration of the data collected, it is therefore not possible to confirm the hypothesis that geographical distance from armed conflict has an impact on the efficiency of banks.

Table 33.
Average values of C/I and NIM ratios and their dynamics in universal banking sectors in CEE countries

	Cost efficiency C/I (%)					Interest margin (%)				
Country	**2019**	**2020**	**2021**	**2022**	**2023**	**2019**	**2020**	**2021**	**2022**	**2023**
average										
Estonia	59.89	69.98	64.39	55.06	46.37	4.96	4.42	3.81	3.96	5.56
Hungary	69.81	70.52	65.06	61.11	54.50	2.17	2.07	2.21	4.06	4.65
Latvia	56.24	66.05	55.32	54.17	40.92	2.79	2.30	2.41	2.64	4.82
Lithuania	48.02	49.09	50.86	45.80	43.84	2.72	2.59	2.49	2.94	4.96
Poland	63.78	77.69	73.72	68.27	61.97	3.63	3.03	2.77	3.90	4.62
Romania	71.10	68.30	65.43	61.22	60.72	4.06	3.76	3.55	3.96	4.43
Slovakia	61.22	63.55	59.89	57.11	50.44	2.46	2.28	2.14	2.07	2.88
Bulgaria	65.69	65.32	63.39	58.54	48.17	4.32	3.84	3.60	3.64	4.84

Cont. table 33.

Czech Republic	47.59	51.86	49.19	40.28	42.70	2.53	2.14	2.05	2.64	2.57
dynamics of change (%)										
Estonia		16.84	-7.98	-14.49	-15.78		-10.89	-13.90	4.06	40.19
Hungary		1.01	-7.73	-6.08	-10.81		-4.87	6.83	83.66	14.51
Latvia		17.44	-16.25	-2.09	-24.45		-17.45	4.88	9.49	82.50
Lithuania		2.22	3.61	-9.95	-4.28		-4.77	-3.85	18.10	68.39
Poland		21.81	-5.10	-7.40	-9.22		-16.50	-8.74	40.85	18.46
Romania		-3.93	-4.20	-6.44	-0.82		-7.26	-5.59	11.40	11.99
Slovakia		3.81	-5.77	-4.64	-11.68		-7.45	-5.97	-3.27	39.05
Bulgaria		-0.56	-2.96	-7.64	-17.71		-11.10	-6.34	1.01	33.17
Czech Republic		8.97	-5.16	-18.11	6.01		-15.11	-4.49	28.83	-2.44

Source: Own study based on Orbis data.

Within the core group of countries analysed, Lithuania and Latvia have been identified as those with the most efficient banking sectors, while Poland, Romania and Hungary have been identified as those with the least efficient. We observe that the nationalised nature of the banking sector is associated with poorer performance by banks in terms of efficiency.

With regard to average interest margin, Slovakia was the only country to maintain one of the lowest margins throughout the entire period under review. This margin was 2.53% at the beginning of the period and 2.57% at the end. Conversely, Estonia was the only country to maintain one of the highest margins throughout the entire period. This margin was 4.96% at the beginning of the period and 5.56% at the end. The classification of both countries as 'globalised' suggests that the delineation made does not signify a distinction in terms of margin level.

In the year the pandemic broke out, the average efficiency of universal banks deteriorated in all the countries analysed except Romania, where the C/I ratio fell by 3.93%. Slight increases in the ratio were recorded in Hungary (1.01%) and Lithuania (2.22%). The most significant deterioration in efficiency was observed in Poland, with an increase of 21.81%, and Lithuania, with an increase of 17.44%. The group of countries where efficiency deteriorated the least as a result of the pandemic and those where it deteriorated the most include countries with globalised and nationalised banking sectors. Consequently, it is not possible to determine which model performed better in terms of efficiency during the pandemic.

In 2022, the greatest improvements in efficiency were observed in Estonia and Latvia, while the least significant improvements were observed in Latvia and Slovakia. These countries are members of the globalised group, thereby rendering the adopted division as an ineffective measure in determining resistance to the external factor of war.

In the year the pandemic broke out, interest margins fell in all the countries analysed – most dynamically in Latvia and Poland (-17.45%, -16.50%), and least dynamically in Lithuania and Hungary (-4.77%, 4.87%). Once again, there is no discernible direction of influence on changes from the greater or lesser openness of the international banking sector.

In the year in which the war in Ukraine broke out, the prevailing trend in terms of changes in interest margins was an increase. It is notable that Slovakia was the only country where the average interest margin of universal banks decreased, by 3.27%. The lowest increase was recorded in Estonia, at 4.06%. The most significant increases were observed in Hungary and Poland, with increases of 83.66% and 40.85%, respectively. This indicates that banking institutions operating within nationalised sectors exhibited a greater propensity to leverage the interest rate increase to augment their revenues compared to those operating within globalised sectors.

To summarise the comparison of the average results achieved by banks from Central and Eastern European countries in terms of efficiency, banks from globalised sectors proved to be more efficient. However, the resilience of efficiency to external e shocks in the form of a pandemic and war did not correlate with either geographical distance or the degree of openness of the sector to foreign influences. In terms of interest margins, the only correlation observed was in the growth rate of margins in the year the war in Ukraine broke out. It grew more strongly in countries with more closed banking systems.

Credit policy

In Table 34, a summary of two indicators is presented which characterise credit policy: the ratio of loans granted to deposits collected, and the share of non-performing loans in the total loan portfolio. Once again, the average values for universal banks in Bulgaria and the Czech Republic, as countries further away from the theatre of war, were taken into account. Neither country demonstrates any particular distinction in relation to the results obtained by countries bordering the conflict. Consequently, the hypothesis that geographical distance from conflict is a significant factor in the shaping of credit policy cannot be substantiated.

Table 34.
Average values of L/D and NPL ratios and their dynamics in universal banking sectors in CEE countries

	Loans to deposits L/D (%)					Loans at risk/Gross loans and advances to customers				
Country	**2019**	**2020**	**2021**	**2022**	**2023**	**2019**	**2020**	**2021**	**2022**	**2023**
average										
Estonia	84.97	77.99	76.55	82.20	80.51	3.73	3.78	1.81	1.85	2.88
Hungary	59.09	52.28	47.25	53.85	52.71	4.06	3.78	3.86	3.50	2.84
Latvia	63.41	56.33	61.78	60.32	63.93	12.23	10.72	9.64	10.61	9.12
Lithuania	73.12	60.27	57.80	63.46	64.94	2.93	3.31	1.95	1.46	1.66
Poland	76.11	69.22	66.59	61.49	57.56	10.62	11.90	11.71	12.24	12.41
Romania	75.21	74.40	73.67	75.03	72.70	5.61	5.14	4.50	3.65	4.14
Slovakia	105.71	104.14	104.44	106.58	103.01	4.37	4.83	4.62	4.09	3.75
Bulgaria	61.49	58.71	58.25	57.86	61.21	13.13	9.81	7.01	5.90	4.45
Czech Republic	55.58	57.61	60.09	61.23	57.16	3.96	4.68	3.69	3.13	2.98
dynamics of change (%)										
Estonia		-8.21	-1.84	7.38	-2.06		1.43	-52.18	2.16	55.92

Cont. table 34.

Hungary		-11.52	-9.61	13.96	-2.12		-6.75	2.14	-9.47	-18.74
Latvia		-11.16	9.67	-2.36	5.99		-12.37	-10.09	10.14	-14.04
Lithuania		-17.57	-4.10	9.80	2.32		13.08	-41.20	-25.10	14.07
Poland		-9.05	-3.81	-7.65	-6.39		12.04	-1.65	4.56	1.36
Romania		-1.08	-0.98	1.84	-3.11		-8.37	-12.45	-18.96	13.48
Slovakia		-1.48	0.29	2.05	-3.34		10.52	-4.30	-11.51	-8.49
Bulgaria		-4.52	-0.79	-0.68	5.80		-25.25	-28.54	-15.93	-24.60
Czech Republic		3.66	4.31	1.90	-6.66		18.28	-21.06	-15.25	-4.73

Source: Own study based on Orbis data.

Within the main group, the countries with banking sectors that most heavily utilise deposits to finance lending are Slovakia and Estonia, while Hungary and Latvia pursue the most cautious policies in this regard at the beginning of the period and Hungary and Poland at the end. It is therefore noticeable that countries with nationalised banking sectors utilise customer savings to a lesser extent to finance their lending activities.

Despite a consistent decline in lending relative to deposits, Polish banks have the highest number of non-performing loans in their entire loan portfolio, and their share has been increasing steadily during the period analysed. The second banking sector with the worst loan portfolio was Latvia, but there the trend was the opposite of that in Poland, with the percentage of non-performing loans falling. Lithuania and Estonia demonstrated the most robust loan portfolios, with Hungary following suit in 2023. As both groups include countries with open and closed banking sectors, it is not possible to determine the impact of this feature on the quality of the loan portfolio.

The countries that demonstrated the most significant decrease in the ratio of loans to deposits in the year the pandemic broke out were Lithuania (17.57%), Hungary and Latvia (11.52% and 11.16%, respectively). The L/D ratio exhibited the least dynamic fluctuations in 2020 within the Romanian and Slovak sectors. Consequently, it is not possible to ascertain the direction of the potential impact of the globalisation of the banking sector on the volume of lending during the initial phase of the pandemic.

In the year in which the war in Ukraine commenced, the L/D ratio exhibited a decline in Poland (by 7.65%) and Latvia (by 2.36%). An increase in the lending activity of universal banks can be observed in other countries. The most notable increases were recorded in Hungary (13.96%) and Lithuania (9.80%). As was previously observed, countries of differing characteristics are evident within both groups.

In the year in which the war in Ukraine broke out, the quality of the loan portfolio deteriorated by10.14% in Latvia by 4.56% in Poland, and by 2.16% in Estonia. Conversely, banks in Lithuania, Romania, Slovakia and Hungary have achieved a reduction in the average value of the non-performing loan ratio by 25,10%, 18,96%, 11,51%, and 9,47%, respectively. Both groups comprise countries that exhibit a higher degree of openness and receptivity to capital and international banking institutions. Consequently, this attribute of the banking sector

does not appear to have exerted a significant influence on the quality of the loan portfolio during the year in which the war erupted.

In conclusion, the comparative analysis of credit policy indicators demonstrates that they exhibit minimal correlation with the degree of openness of sectors to foreign influence. The sole correlation that was identified is a lower L/D ratio in countries where local authorities exert a greater influence on the banking sector.

5. Discussion

A comparative analysis of the profitability, efficiency and credit policy of universal banks operating in CEE countries between 2019 and 2023 does not provide grounds for accepting the hypothesis that the banking sectors of countries bordering the participants in the conflict in Ukraine were more exposed to the impact of the outbreak of this conflict on the global economy than countries not bordering Ukraine or Russia.

With regard to profitability, the Czech banking sector demonstrated higher levels of return on equity throughout the period under analysis but the dynamics of changes in 2022 did not distinguish it from other countries. With regard to efficiency, a more dynamic improvement in the cost efficiency ratio was observed in the Czech Republic in 2022; however, the dynamics of this ratio in Bulgaria were comparable to those in other countries. With regard to the credit policy, no extreme values were observed for the group under study. The disparities are too insignificant to infer that the mere proximity to conflict constituted a variable that exerted a substantial influence on the outcomes attained by the banking sectors in Central and Eastern Europe.

The findings obtained for the initial hypothesis are in alignment with the preceding research conducted by Martins, Correia, and Gouveia (2023), which determined that the decrease in bank share prices in Europe was predominantly influenced by exposure to Russia, as opposed to geographical distance from the conflict. This assertion is corroborated by also the research of De Haas, Mamonov, Popov and Shala (2025), which found no evidence of credit shocks spilling over to neighbouring countries. However, the present study is in opposition to the findings of Federle, Meier, Müller and Sehn (2024), who found a 'penalty for proximity' (each +1000 km from Ukraine increased stock market returns by 2.6 percentage points). The observed discrepancy in the results may be attributable to the utilisation of divergent definitions of distance from the combat zone. The Federle et al. study provided a precise definition in kilometres, while in the above studies, the sole differentiating factor was the fact of bordering on the participants in the conflict. They also do not coincide with the results of Silva, Wilhelm, and Tabak (2023). Their research indicates that in Europe, the intensity of market responses is predominantly influenced by proximity to the conflict, rather than by trade considerations.

In this particular instance, the observed discrepancy may be attributed to the geographical scope of the study area, which encompasses the CEE region but not the entirety of Europe. A similar rationale underpinning the observed variations in outcomes is also applicable to Pham, Talavera and Tsapin (2018). The present study focused on the area of the country affected by the conflict itself, rather than on several countries that only border the participant in the conflict.

We managed to observe certain interdependencies between the profitability of individual banking sectors and their degree of openness to foreign capital and international financial institutions. In countries where this influence is most prominent, a reduced level of volatility was observed. During the pandemic, profitability in these countries declined to a lesser extent, and during the war it increased to a lesser extent. This may lead to the conclusion that in this region of Europe, greater political influence on the banking sector leads to greater volatility in bank profitability.

This finding aligns with the conclusions of Goniszewski (2023), which demonstrated that banks under state control exhibit heightened vulnerability to suboptimal decision-making during crises, resulting in increased volatility in profitability. Miklaszewska et al. (2021), Kozak (2021), Węgrzyn, Topczewska (2023) and Badics (2023) also indicated that banks with a strong state share reacted with greater declines in profitability during the period of the pandemic, which is consistent with the hypothesis.

However, no correlation was observed between the level of profitability and the openness of the sector. Poland was the country with the lowest average profitability of universal banks, while Hungary had the highest average return on equity for most of the period analysed. In both countries, the banking sector is subject to significant government influence, which may lead to the conclusion that nationalisation of the banking sector contributes to unpredictability in terms of profitability. The outcomes of such measures can be highly favourable or extremely unfavourable, a phenomenon that is likely contingent upon the quality of the state institutions in question, as indicated by the results achieved by Bertay et al. (2015) and Chen et al. (2016).

A comparative analysis of the efficiency of banking sectors in the CEE region revealed a correlation between higher cost efficiency and a more globalised nature of the universal banking sector. As has been noted previously, the Polish universal banking sector, which is subject to the greatest political influence, once again produced the worst results in this respect. These results are consistent with those reported in earlier studies: As demonstrated in the works of Goniszewski (2023), Miklaszewska et al. (2021), Kozak (2021), Węgrzyn, Topczewska (2023), Badics (2023), and Karaś, Boda (2024). However, an analysis of the resilience of efficiency to external shocks demonstrated no correlation with the nature of the banking sector. With regard to the correlation between interest margins and the growth rate of margins, it was observed that there was a relationship in the year of the outbreak of the war in Ukraine. The phenomenon exhibited a heightened degree of growth in countries characterised by more closed banking systems, a development that once again points to the possibility of greater volatility in this group.

In the final group of indicators analysed – credit policy indicators – the lowest correlation with the openness of sectors to foreign influence was identified. The only observed correlation is a lower L/D ratio in countries with greater local government influence on the banking sector. This may be considered surprising given that one of the arguments for nationalising these sectors was to provide consumers and businesses with easier access to credit financing. The findings pertaining to the heightened credit constraints imposed by state-controlled banking institutions are in alignment with the outcomes documented by Miklaszewska et al. (2021), Kozak (2021), and Węgrzyn and Topczewska (2023). These findings stand in contrast to the results reported by Badics (2023).

It was also observed that the banking sector in Poland exhibits the poorest results in terms of the quality of its loan portfolio. The finding that the banking sector in this country obtained the poorest results in the examined group with regard to both profitability and efficiency, in addition to credit policy, may signal the necessity to reconsider the strategy of substantial state capital involvement in the banking sector and sticking to the local currency and, consequently, monetary policy as a guarantee of optimal conditions for the functioning of the economy.

6. Conclusions

The study does not provide grounds for accepting the hypothesis that the banking sectors of CEE countries bordering Ukraine and Russia reacted more dynamically to the start of Russia's full-scale war with Ukraine in terms of changes in profitability, efficiency and lending than other countries in the region that do not border the parties to the conflict. This result may be indicative of the CEE region being sufficiently homogeneous and relatively small in area, thereby negating the so-called 'penalty for proximity' within it. This phenomenon can only be observed in studies that encompass the entire European continent.

However, the results obtained provide grounds for hypothesising that there is a correlation between the results achieved by banks and the level of state capital involvement in the banking sector. The universal banking sectors of CEE countries, which are more dependent on the decisions of national institutions, achieved more volatile profitability results during the pandemic crisis and the shock following the outbreak of war in Ukraine. During the pandemic, profitability experienced a precipitous decline, while during the outbreak of the war, it exhibited a more pronounced increase compared to CEE countries, where the banking sector was more influenced by foreign capital. The study revealed a negative correlation between the degree of political influence exerted on the banking sector in CEE countries and the subsequent performance of the banks in terms of efficiency. Furthermore, restrictions were imposed on

lending, yet no evidence was found to suggest that this was associated with an improvement or deterioration in the quality of the loan portfolio.

At this stage of research into the financial condition of the banking sectors in CEE countries, the results obtained provide a basis for recommending a reduction in the influence of local political factors on bank management and indicate the positive impact of the internationalisation of the banking sector on the stability and efficiency of banking.

In the subsequent phase of the research, the present descriptive study should be supplemented with statistical and econometric methods. The implementation of these methods will facilitate the verification of relationships between factors and augment the evidential value of the results. Furthermore, the incorporation of additional variables will enable the explanation of the diversity of results observed in the banking sectors of CEE countries.

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THE USE OF ARTIFICIAL INTELLIGENCE IN EDUCATION BY STUDENT

Magdalena GORZELANY-DZIADKOWIEC[1*], Krzysztof MACHACZKA[2], Małgorzata MACHACZKA[3]

[1] Cracow University of Economics; gorzelam@uek.krakow.pl, ORCID: 0000-0001-9062-5984
[2] Cracow University of Economics; machaczk@uek.krakow.pl, ORCID: 0000-0002-7345-122X
[3] Cracow University of Economics; machaczm@uek.krakow.pl, ORCID: 0000-0001-8194-0990
* Correspondence author

Purpose: The purpose of the study is to identify areas of student use of Artificial Intelligence (AI) in education, as well as to develop a model view of student use of AI in education.
Design/methodology/approach: The study used an integrated research approach, combining descriptive, comparative and descriptive analysis methods to provide an in-depth and multifaceted understanding of the role and potential of artificial intelligence in education. The research process started with a biblio-metric analysis and a systematic literature review, which was conducted in Scopus and Google Scholar databases. The literature analysis carried out allowed artificial intelligence to be defined, as well as selected AI tools to be identified. Subsequently, an in-house study was carried out, which was in the form of a survey - a diagnostic poll; authors' questionnaire containing ten closed questions was used as a research tool. The questionnaire was uploaded to Google and the link was distributed to selected students of Cracow University of Economics in Krakow. Responses were collected using the CAWI technique. A total of 295 responses were obtained.
Results: It was found that students use AI in education, the main areas of use of AI tools by students are: writing term papers, reports, or creating presentations. What is very important, students use AI to obtain feedback on their work, and are also aware of the benefits and threats generated by modern technologies. The conducted research allowed for the development of a model approach to the use of AI in education by students.
Research limitations/implications: The study was limited by the sample of people studying at Cracow University of Economics in Krakow. The authors showed that students use AI in education to a large extent, ChatGPT was most frequently indicated as the tool of preference, as well as the frequent use of Gemini by students. Students indicated risks as well as benefits of using AI in education which allowed the authors to conclude that they use AI consciously. Future research should include a more in-depth exploration of the directions of AI use in education and investigate the impact of AI on competence development. Research on the attitudes - behavioural, cognitive, emotional - of students towards ChatGPT may also be interesting, as well as examining the differences in attitudes depending on the field of study.
Practical implications: The development of a model for the use of artificial intelligence in education by students can indicate current trends in education that are posed to both lecturers and students to adapt to changing market and educational conditions.

Social implications: There is an increased awareness among lecturers and students regarding the use of AI in education and its impact on the sector.
Originality/value: Discussion of AI, identification of AI tools, identification of the extent and areas of student use of AI in education. The added value is to identify the benefits and risks of student use of AI in education, as well as to develop a model view of student use of AI in education.
Keywords: artificial intelligence, AI in education, AI in student education, student education, benefits of using AI, threats from the use of AI.
Category of work: academic paper, own research (diagnostic survey).

1. Introduction

Artificial intelligence (AI) is one of the most important trends shaping modern reality, and education is one of the areas where it plays a key role. AI can make the learning process easier, more efficient and more effective at all levels, for the student, the teacher and the education system as a whole. Learners assimilate knowledge and skills faster and with less effort, and can do so at a time and place that is convenient for them. However, it is important to remember that the integration of artificial intelligence into the educational process also raises numerous concerns. In this new set-up, the natural interpersonal relationships that play an important role in the education and socialisation process are reduced or even absent. Teachers do not want to be reduced to the role of technological guardians. AI is a powerful educational tool that has the potential to radically change the way in which we teach and learn. In the era where technology is rapidly changing, it is crucial that education does not lag behind, but evolves with it.

The traditional role of education is to prepare learners for the future. This future, in turn, appears today as a constant change in learning and working environments, which are increasingly filled with technology aiming to replace routine work with automated procedures and devices (Sysło, 2022). The phenomenon of artificial intelligence takes on particular relevance in the context of contemporary educational challenges, such as adapting to the diverse needs of students, the effective transfer of knowledge and the continuous improvement of teaching methods. In the light of these challenges, artificial intelligence becomes not only a tool to facilitate the learning process, but also a dynamic partner, capable of adapting to the individual's predispositions of students (Zalewska-Bochenko, 2024).

For the reasons mentioned above, technological advances as well as the use of AI in education by pupils, or students, will not be avoided. Instead, it is important to find out the scope, of the tools and extent to which students use AI in education, as well as to explore their awareness of the benefits and the risks of using AI.

2. Artificial intelligence, definitional scope

AI is a new, important and relatively unexplored area, and many AI applications have limited or no use due to ethical concerns and lack of trust from their users (Miller, 2019) demonstrates the ability to analyse vast amounts of data, which supports the creation of predictions, discovering patterns and generating insights in various design activities (Han, Childs, Luo, 2024).

AI is set to be one of the most important technologies of the future. The Committee of the Council of Ministers for Digitalisation adopted the 'Policy for the development of artificial intelligence in Poland' in 2020. The document sets out activities and goals for Poland in the short term (until 2023), medium term (until 2027) and long term (after 2027). Among the six areas, the document mentions education: "AI and education, actions taken from primary education up to the university level and course programmes for people at risk of losing their jobs due to the development of new technologies and educational grants" (Fazlagić, 2022).

A multitude of definitions of artificial intelligence can be found in the literature. Zalewska Bochenko (2024) points out that AI is a term that takes on different meanings depending on the context and perspective, and the definitions are as diverse as its applications. S. Koziej (2023) considers AI to be problem solving, decision making, data-driven learning, natural language understanding, image and sound processing, and many other tasks that were previously reserved for the human mind. On the other hand, T. Zalewski (2020) understands artificial intelligence as a system that allows us to perform tasks that require a learning process whilst taking into account new circumstances in the course of solving a given problem, which can, depending on its configuration, act autonomously and interact with the environment to varying degrees. M. Warszycki (2019) points out that AI is an area of science that brings together disciplines, methods, tools and techniques aimed at creating and developing a complete computer programme that will accurately reflect a model of how humans and their minds function. The main processes and functions it should perform are: inference and pattern finding, reasoning, learning from experience, using acquired information, non-accidental and non-random planning of activities, creativity, problem solving and autonomy in decision-making.

Today, artificial intelligence can be found in everything from smartphone cameras to video games, e-commerce, education, healthcare, cybersecurity, product recommendations, search engines or advertising (Fintech article 2022). The scope of the use of AI is broad, with researchers highlighting the use of AI in design, particularly for various design activities. This includes supporting idea’s and concept generation (Luo et al., 2018; Sarica et al., 2021; Hanifi et al., 2022), concept and product evaluation (Chen et al., 2021), design simulation (Uddin et al., 2019), data analysis (López et al., 2019) and design automation (Kang et al., 2023).

Recently, large language-based artificial intelligence models such as OpenAI's GPT-3 and GPT-4, Google's Gemini and Meta's LLaMA, which have extensive common knowledge and powerful semantic reasoning capabilities, have been used to support design (Han, Childs, Luo, 2024).

AI is also transforming the world of education, opening up new possibilities for teaching and learning. Thanks to AI, education is becoming more personalised, adapting to each student's individual needs and learning styles.

Alongside advances in AI technologies, with human abilities such as learning, adaptation, self-correction and complex problem solving (Chen et al., 2023), the application of AI in education has attracted increasing attention due to its potential to transform educational practices in both classroom settings and distributed learning contexts (Wu, Wang, Wang, 2024; Gao, Wang, Wang 2024; Huang, Wang, Zhang, 2024; Wang, Reynolds, 2024). For example, Wu, Wang and Wang's (2024) study of factors that influenced students' intention to reuse AI highlighted the potential of AI to remotely support language learning. Huang, Wang and Zhang (2024) linked the generative acceptance of AI to students' digital learning wellbeing and self-efficacy. The popularity of AI in education has revealed research on innovations in teaching and learning that take into account the status of individuals and the need to deepen their engagement (Zhou, Hou, 2024).

AI-based tools enable more effective and interactive learning experiences, facilitate access to knowledge, but also support the development of critical thinking and creativity. The introduction of these innovative technologies is opening new horizons in the way we teach and learn in the 21st century. Suggestions for a selection of the most useful AI tools created with Microsoft Bing for AOL.co.uk that offer’s new learning methods and pathways for the authors as presented in Table 1.

Table 1.
Selected most useful AI tools

AI Text Tools	
ChatGPT	A conversational AI App that can talk to users about a variety of topics and provide detailed answers based on a question.
Jasper AI	A natural text generation platform that can create high-quality content for a variety of fields and purposes, such as marketing, sales, education, etc.
WriteSonic	Tool for creating content, articles, landing pages.
AI Business Assistants	
Grammarly	An online writing assistant that helps correct grammar, spelling, style and tone of text, as well as suggesting better words and phrases.
Rewind AI	It remembers everything that was on your computer screen, your laptop or phone. You type in a keyword and it tells you where and when you saw it.
Compose AI	A browser extension that allows you to write faster and better with intelligent context-based text suggestions.

Cont. table 1.

Graphic AI systems	
MidJourney	Best for generating high-quality creative graphics.
Leonardo	A platform for creating and editing graphics using artificial intelligence to manipulate images, colours and styles.
Dall-E 3	A model for generating images from natural text that can produce unusual and creative visualisations of different concepts and scenarios.
Google AutoDraw	Artificial intelligence drawing tool that automatically enhances and completes user's sketches with professional icons and graphics.
Conversion of Speech to Text	
Otter AI	An AI-enabled meeting assistant that records audio, writes notes, automatically captures slides and generates summaries.

Source: based on authors' research.

In addition to the tools listed in Table 1, it is also worth mentioning tools such as: Video AI editing (Runway, Papercup, Gling), AI music tools (Suno AI, Mumbert, Emergent Drums, Pop2piano), text-to-speech conversion (Eleven Labs, Veed IO, Murf), information extractors (Browse.ai, Import.io, Snorkel Flow), code correction (Kodezi, Replit, Copilot). The tools indicated above are far less frequently used in education than those shown in the table.

3. Materials and methods

The study uses an integrated research approach, combining descriptive, comparative and descriptive analysis methods to provide an in-depth and multifaceted understanding of the role and potential use of artificial intelligence in education.

The research process started with a biblio-metric analysis and a systematic literature review, which was conducted in Scopus and Google Scholar databases. Articles were filtered based on the purpose of the research. Articles were searched using the following keywords: artificial intelligence, AI in education, AI tools. The literature analysis was conducted from January 2025 to 15 March 2025. The literature analysis carried out allowed artificial intelligence to be defined, as well as selected AI tools to be identified. The analysis also identified a gap of knowledge, which is the lack of identified areas of student use of AI in education, as well as the lack of a model view of student use of AI in education.

Therefore, in the next stage of the research, a questionnaire was developed on the basis of the literature review carried out to identify the areas detrimental to the students' use of AI in education. Respondents answered the questionnaire using a five-point Likert scale. Using the Likert scale (1932) allows researchers to detect even relatively subtle differences in the attitudes under study. The advantage of this scale over simple scales is also evident in the fact that the individual items on the scale are not able to significantly influence the final outcome of the measurement. The items are supposed to balance each other, given the scale being constructed, whereas the particular properties of a simple scale can have a major impact on the conclusions drawn from the research. In rank methods, the normalisation procedure involves ranking the

objects according to an ordering criteria adopted for the variable in question. Then, variants of the variable are assigned ranks, i.e. conventional numerical values, which are most often the ordinal numbers of the places occupied by the objects in the ordered series (Tarka, 2015). Accordingly, this study assumes that 1 means to a very low degree and 5 means to a very high degree.

To examine the relationship between variables, the Spearman rank correlation coefficient was calculated to check for linear and monotonic relationships. Additionally, the Mann-Whitney test was used for analysis.

The in-house research took the form of a survey, a diagnostic poll, and an original questionnaire containing ten closed questions was used as the research tool. In order to validate the questionnaire used for the study, a pilot study was conducted, in which the understanding of the questions contained in the questionnaire and the correctness of their content were asked. The questionnaire was uploaded to Google and the link was distributed to students at Cracow University of Economics in Krakow. Responses were collected using the CAWI technique. A total of 295 responses were obtained. The research was aimed at identifying areas of AI use in education by students, as well as developing a model view of AI use in education by students. The following research questions were formulated to realise the stated aim: do students use AI in education? which AI tools and to what extent do students use AI in education? In which areas do students use AI and to what extent? What benefits does the use of AI bring to students? What are the risks of using AI according to students? The research provided a comprehensive overview of current trends and research in the area of student use of AI in education, as well as an attempt to model the phenomenon in question. Furthermore, inductive reasoning was used in the analysis, which made it possible to generate general conclusions on the basis of detailed observations and analyses. This approach was crucial for formulating directions for further research and future directions for the development and impact of AI on education. Each of the methods used made a significant contribution to the comprehensive analysis of the issue, enabling an understanding of its various aspects.

4. Results

A total of 295 correctly completed questionnaires were obtained. The persons surveyed were representatives of various first and second degree courses. The structure of the persons surveyed by field of study is illustrated in Figure 1.

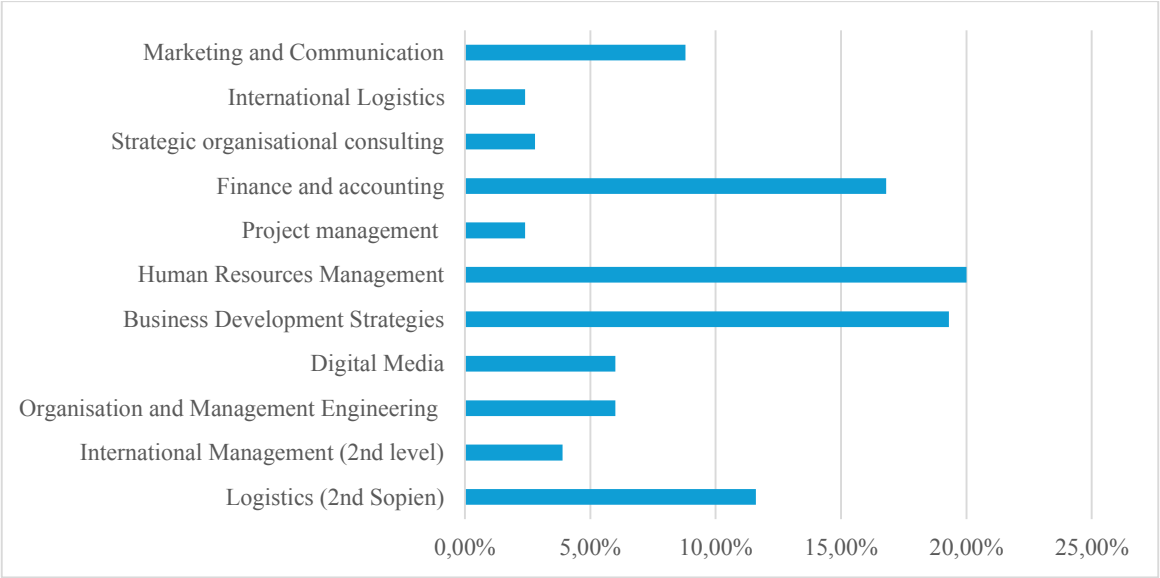


Figure 1. Structure of the surveyed students by a field of study.

Source: own compilation based on conducted surveys.

When analysing the summary presented in Figure 1, it can be seen that the largest group of respondents were students of Human Resource Management (20% of respondents) and Business Development Strategies (19% of respondents), followed by Finance and Accounting (nearly 17% of respondents), Logistics (nearly 12% of respondents), Marketing and Communication (nearly 9% of respondents), Digital Media and Organisation and Management Engineering (6% of respondents each). Representatives of first degree programmes accounted for 84.5% of respondents, while second degree programmes accounted for 15.5% of respondents.

As the Spearman correlation coefficient did not show statistical significance between the answers of the representatives of the different fields of study in the responses obtained, the results of the study are summarised.

The first question concerned students' perceptions of artificial intelligence, with 85% of those surveyed indicating that AI was one of the most important technologies of the future (7.5% of those surveyed stated that it was not and 7.5% had no opinion). Another question in the questionnaire concerned the use of AI by students in education. The survey allows the authors to conclude that students are using AI in education, with 66.3% of the respondents answering yes (24.9% indicated that they are using it to a very great extent, 41.4% indicated that they are using it to a great extent). In addition, it was determined that AI is used by 25.3% students to a partial extent, to a small extent by 7.4% of respondents and only 1% - 3 persons indicated that they use AI for educational purposes to a small extent.

The next question asked in the questionnaire was about the AI tools that students use. The results are illustrated in Figure 2.

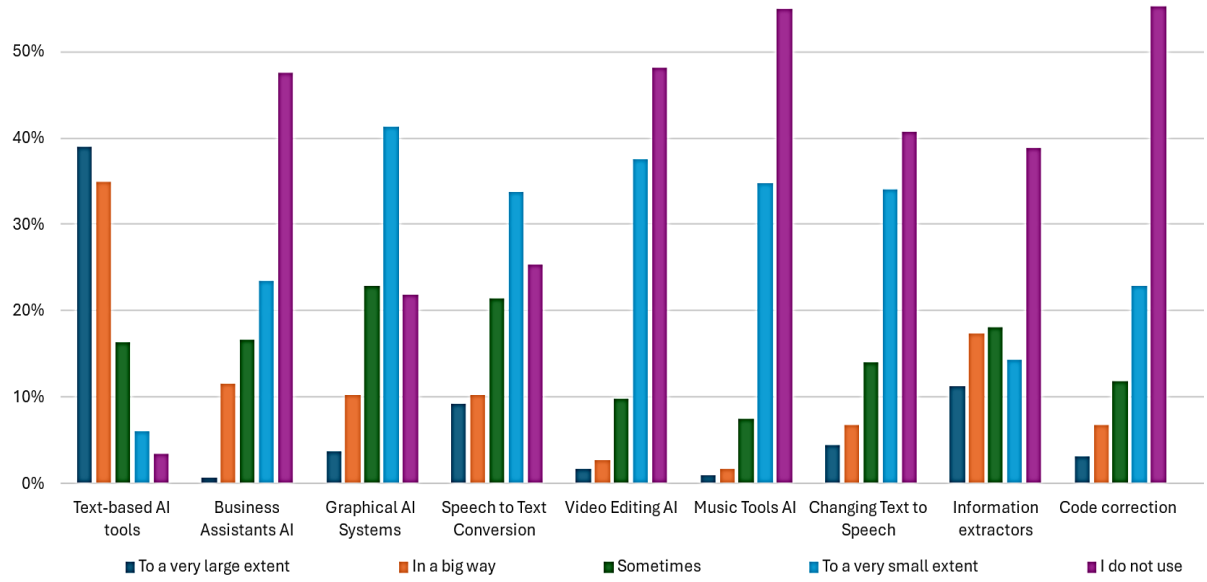


Figure 2. Structure of AI tools used by students.

Source: own compilation based on surveys conducted.

When analysing the summary shown in Figure 2, it was found that students identified that they use text-based AI tools, with 74% of respondents answering that they use these tools to a very high or high degree. Graphical AI Systems and Speech to Text Conversion are tools used to a low degree so specified by more than 40% and 30% of the respondents, while unfamiliarity with these tools was indicated by only about 22%-25% of the respondents. Other AI tools such as Business Assistants AI, Video Editing AI, Music Tools AI, Changing Text to Speech about 40-50% of the respondents indicated that they use this tool to a very small extent or are not familiar with it at all. The AI tools least known by students were code correction and music tools so specified by more than 50% of respondents.

In the next question, students were asked to indicate which AI tools they use and to what extent. The research showed that students use ChatGPT in education to a very high degree, 114 students, 103 respondents indicated that they use ChatGPT to a high degree. This led to the conclusion that ChatGPT is used to a great extent in education by students, this was indicated by 75% of the people surveyed. Tools such as Jasper AI, WriteSonic, Rewind AI, Compose AI, Otter AI, MidJourney, Leonardo, Dall-E 3, Google AutoDraw are not known by the surveyed students, and between 83 to 90% of respondents indicated that they are not familiar with these tools. In addition to the tools indicated in the questionnaire, 75% of the surveyed students indicated that they do not use other AI tools in education, while about 10-15% of the surveyed students indicated that they use Perplexity and Gemini. Perplexity AI (Perplexity), is a US-based web search engine that uses a large language model to process queries and synthesise answers based on web search results (Roduner, 2023). Using a conversational approach, Perplexity allows users to ask follow-up questions and receive answers with links to sources from the web (Wiggers, 2023). Gemini, previously known as Bard, is an artificial

intelligence chatbot developed by Google. In 2022, OpenAI launched ChatGPT, and Google responded by launching Bard and its successor chatbot Gemini (Konrad, Cai, 2023).

In the next question, students identified in which areas and to what extent they use AI in education. The results are illustrated in Figure 3.

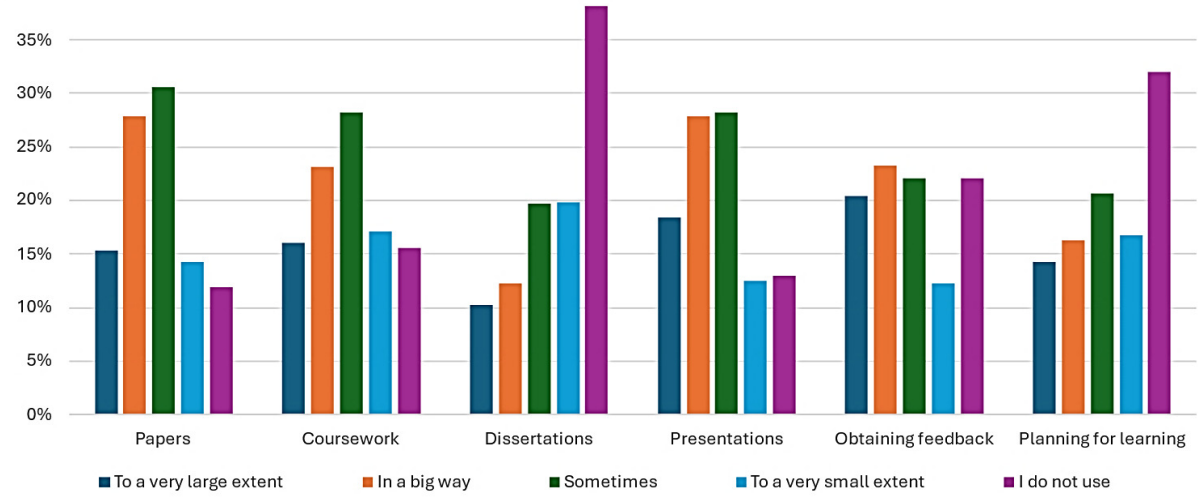


Figure 3. Areas of student use of AI in.

Source: own compilation based on surveys conducted.

When analysing the summary of results in Figure 3, it was found that the most common use of AI tools by the students surveyed is to create presentations, with 46.3% of the respondents responding in this way (18.4% of the respondents stated that they use AI to create presentations to a great extent, while 27.9% of the respondents stated that they use it to a lesser degree). Another area of students' use of AI tools in education is writing papers and getting feedback on their work, nearly 44% of respondents answered that they use AI in these areas to a very great and great extent. Students' use of AI tools for writing assignments is partial, the modal value and the most frequent value in this area is depicted in figure 3. Nearly 40% of the respondents indicated that they use AI for assignments to a very high or high degree, a similar percentage of about 33% of the respondents stated that they use AI tools for assignments to a very low degree or not at all. An interesting result was obtained in the area of students' use of AI tools for thesis writing (bachelor's, engineering, master's). The vast majority, 57.9%, of respondents declared that they use AI very little or not at all for thesis writing (38% indicated that they do not use AI for thesis writing). The modal value in this area is 1. Due to this result, it was hypothesised that second-degree students make greater use of AI tools for thesis writing. In order to verify this thesis, Spearman ranked correlations were calculated, which showed that there is no linear or monotonic relationship between these variables, regardless of whether someone is in a first or second degree, the level of use of AI is very similar. Test results: Correlation = -0.0072 p-value = 0.9043 In addition, an analysis with the Mann-Whitney test was performed and confirmed that: there is no statistically significant difference in the declared level of AI use between Level I and Level II students. Test results: Value of test statistic (W):

5038 p-value: 0.9049. Therefore, the thesis statement was rejected, as it was found that students do not use AI tools to the same extent in writing their theses at both first and second degree.

Another question included in the questionnaire concerned the verification of AI-generated material for content. 65% of the surveyed student's always check the generated material, 31% of the surveyed students do so sometimes, while only 4% of the surveyed students rarely and never check the AI-generated material. This allows us to conclude that students are consciously using AI tools and are also aware of the mistakes that the technology can make.

The questionnaire closed with questions on the benefits and risks of students using AI in education. The following scale was adopted: 5 - very high benefit/risk, 4 - high benefit/risk, 3 - partial benefit/risk, 2 - low benefit/risk, 1 - very low benefit/risk. The results in percentage terms are illustrated in Table 2.

Table 2.
Benefits and risks of using AI in education by students

BENEFITS OF AI	Evaluation				
	1	**2**	**3**	**4**	**5**
Interactive tutoring (AI helps with understanding the material, answering questions)	4,4	2,7	17,3	39,8	35,8
Development of soft skills (e.g. management of emotions, problem solving)	18	22,4	27,5	20,4	11,6
Language learning	5,4	11,2	25,9	30,6	26,9
Searching for information	2,4	1	10,5	29,9	56,1
Assistance with tasks	1,7	2,7	9,5	34	51
RISKS OF USING AI					
Lack of critical thinking	1,4	2,7	16	33	46,6
Lack of trust in AI	4,4	13,9	35	29,6	1,7
Lack of social interaction	5,5	13	23,5	27	31
Addiction to technology	3,4	3,4	11,6	28,9	52,7
Lack of empathy and understanding	7,1	16,3	25,5	23,8	27,2
AI manipulation	3,4	9,5	19	30,6	37,4
Ethical challenges and privacy risks	3,4	8,8	20	31	36,7
Disinformation generated by AI	3,4	3,4	10,2	28,6	54,4

Source: own compilation based on surveys conducted.

After analysing the summary presented in Table 2, it was found that the surveyed students were among as the biggest beneficiaries of using AI tools in education to identify information retrieval and assignment help, more than 50% of the surveyed people identified this as a very big benefit, while about 30% identified it as a big benefit. Among the benefits of using AI tools, students identified interactive tutoring (more than 75% of those surveyed) and language learning (more than 50% of those surveyed so indicated). According to the students surveyed, the biggest threats to the use of AI tools are the lack of critical thinking. Nearly 47% described AI as a very big threat for dependence on technology and misinformation generated by AI with a lack of social interaction, lack of empathy and understanding, manipulation by AI, and ethical challenges and threats to privacy are also threats, according to respondents.

5. Discussion

The research conducted has helped to confirm that studies indicating that AI is one of the most important technologies of the future (Makridakis, 2017). One area where AI is playing an increasingly important role is education. The implementation of AI-based technologies in the teaching and learning process opens up new horizons and brings both promising opportunities and serious risks (Saputra et al., 2023).

The research conducted did not confirm that students' use of a wide range of AI tools in education. The students surveyed indicated that they use text-based AI tools, of which ChatGPT plays a key role. Although AI technologies in education have the potential to transform traditional teaching models, adapting them to a variety of learning styles and paces, students use these tools cautiously. They recognise the potential of AI to individualise the learning process (Kowalczyk, 2023), but they also recognise the risks that flow from the use of AI tools. AI introduces many innovative solutions in education that have the potential to shape future generations. The benefits of their introduction are invaluable for adapting the educational process to the needs of each pupil (Zalewska-Bochenko, 2024), or student. AI offers the possibility to search for information, get help in solving tasks or get feedback on one's work, but it also carries risks. It is important to recognise the potential risks that may arise from, for example, over-reliance on AI. In the context of shaping future generations, it is crucial to find a balance between harnessing the benefits of AI and preserving the essential aspects of traditional education that shape social skills, empathy and critical thinking skills. Responsible and conscious implementation of AI technologies in the education system will have a decisive impact on the development and preparation of young people for future challenges (Zalewska-Bochenko, 2024). The research conducted allows us to conclude that students, despite their familiarity with AI, maintain this balance, use the tools, but are aware of the risks the technology brings.

The above considerations allowed us to develop a model approach to the use of AI in education by students, which is illustrated in Figure 4 below.

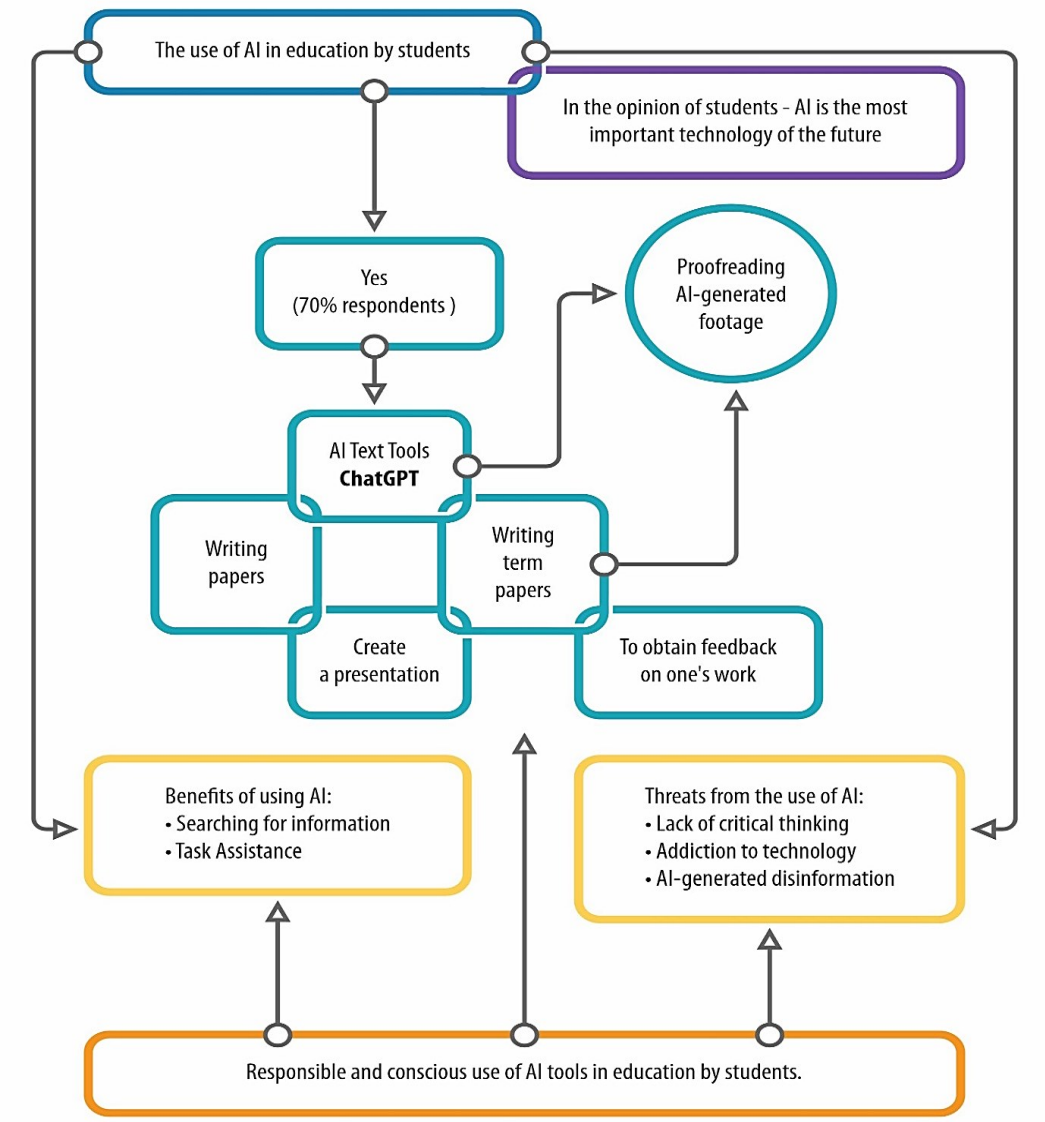


Figure 4. Model approach to the use of AI in education by students.

Source: own study based on conducted research.

The study of the degree of use of artificial intelligence in the educational process is becoming extremely important, as it has the potential to improve tools supporting students in achieving educational success. The use of artificial intelligence, such as speech recognition, spelling correction and automatic generation of suggestions, can provide additional support to students, helping them overcome difficulties whilst adapting the learning process to their individual needs (Więckiewicz-Modrzewska, 2024). Studies have shown that students use AI in education, these tools help them write term papers, reports or create presentations. It is very important that students use AI to obtain feedback on their work whilst being aware of the benefits and threats generated by modern technologies.

6. Conclusions

The areas where AI is being used in education by students has been identified, and a model approach to the use of AI in education by students has been developed.

In answer to the research questions posed, it should be stated that students use AI to a very large extent in education. The most common tool that they use is an AI text tool called ChatGPT. AI is most often used by students to write papers, term papers, create presentations, or obtain feedback on their work. Research has shown that students do not use AI to write theses. The potential benefits identified in the study from the use of AI include searching for information and assistance with tasks. Among the threats, students indicated, a lack of critical thinking, addiction to technology and disinformation generated by AI.

The study was limited by the sample of people studying at UEK in Krakow. Future research should include more in-depth analyses in the directions of use of AI in education and examining the impact of AI on the development of competences. Research on the attitudes including behavioral, cognitive and emotional effects on students towards ChatGPT may also be interesting, as well as examining the differences in attitudes in the field of study. Developing a model for the use of artificial intelligence in education by students may indicate current trends in education, which challenged both lecturers and students to adapt to a changing market and educational conditions.

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MILLIONAIRE OR BROKE? POTENTIAL THREATS FOR CONSUMERS RELATED TO USING FOOD SUPPLEMENTS

Katarzyna HYS

Department of Biosystems Engineering and Chemical Processes, Faculty of Production Engineering and Logistics, Opole University of Technology; k.hys@po.edu.pl, ORCID: 0000-0003-0800-2804

Purpose: The purpose of this paper is to identify the threats resulting from the use of food supplements by individual consumers.
Design/methodology/approach: I conducted a literature review of documented cases describing potential threats associated with the consumption of food supplements. The analysis of these cases allowed me to propose a preliminary classification of the identified risks.
Findings: The study indicates that there is a broad spectrum of potential threats for consumers of food supplements. Preliminary findings suggest that these risks are universal and align with conclusions drawn by researchers examining their national markets. However, the current knowledge remains fragmented and dispersed, which highlights the need for its further systematisation.
Research limitations/implications: As this is an exploratory study based on literature review, the findings are limited by the scope and quality of the available publications. Further empirical research is necessary to validate and expand the proposed classification of threats.
Practical implications: The study underlines the importance of strengthening legal regulations concerning food supplements in order to reduce risks to consumers' health and safety. It also encourages international dialogue on harmonising standards across markets.
Originality/value: This paper provides a structured classification of threats associated with food supplements based on existing literature. It contributes to the discussion on consumer safety and highlights the need for more detailed and coherent legal frameworks regulating the food supplements market.
Keywords: food supplements; threat categories; individual consumer; regulations.
Category of the paper: research paper.

1. Introduction

The authors' previous multi-dimensional analysis of the conditions in the food supplements market became a foundation for conducting in-depth studies in this field (Hys et al., 2022; Hys, Koziarska, 2020, 2021; Hys, 2018, 2019, 2020). General conclusions from previous studies give rise to the statement that consumers do not have sufficient knowledge about potential

threats resulting from using food supplements. Consumption is continuously increasing (Mordor Intelligence Report, 2023). Growth in Poland is shown in Figure 1 (PMR Market Experts, Industry Report, 2023).

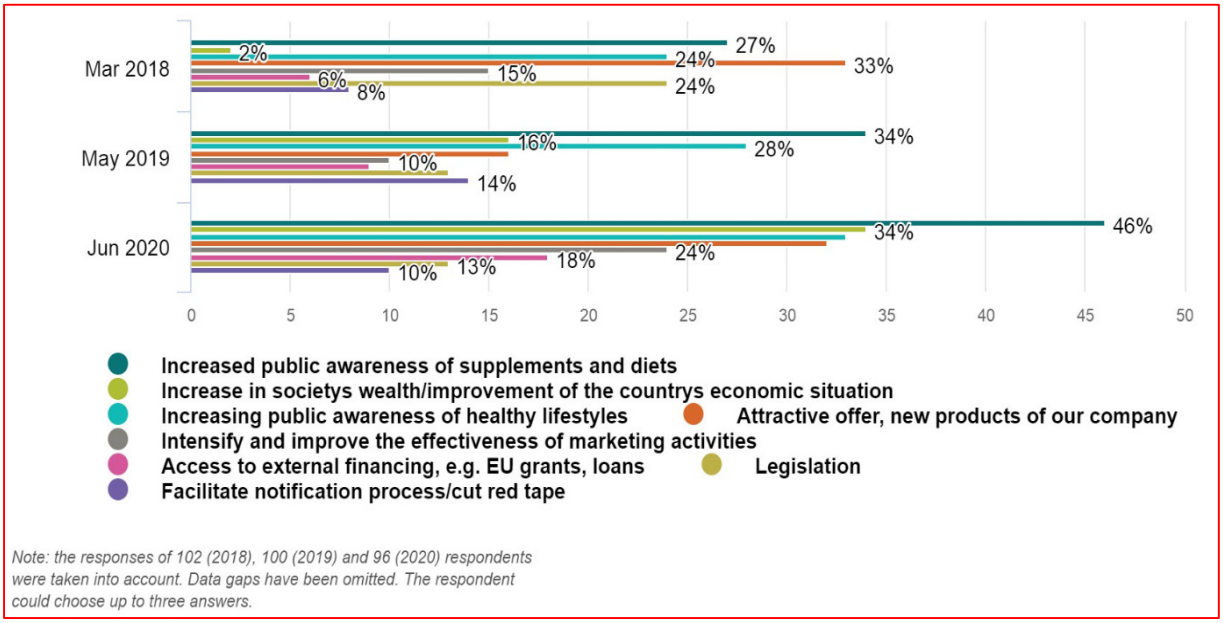


Figure 1. The most important factors in the development of companies operating on the market of dietary supplements in Poland (%), 2018-2020.

Source: (PMR Market Experts, Industry Report, 2023).

However, it is difficult to estimate the effects of huge consumption of food supplements, because no complex studies are conducted in this regard (FDA, 2023; Bailey et al., 2013; Baile et al., 2013). The food supplements market is growing dynamically, because for many years consumers have been receiving information that food supplements are the basis for prevention or a remedy for maintaining of personal health (mental and physical), and in consequence - for longevity; Figure 2 (Dickinson et al., 2014).

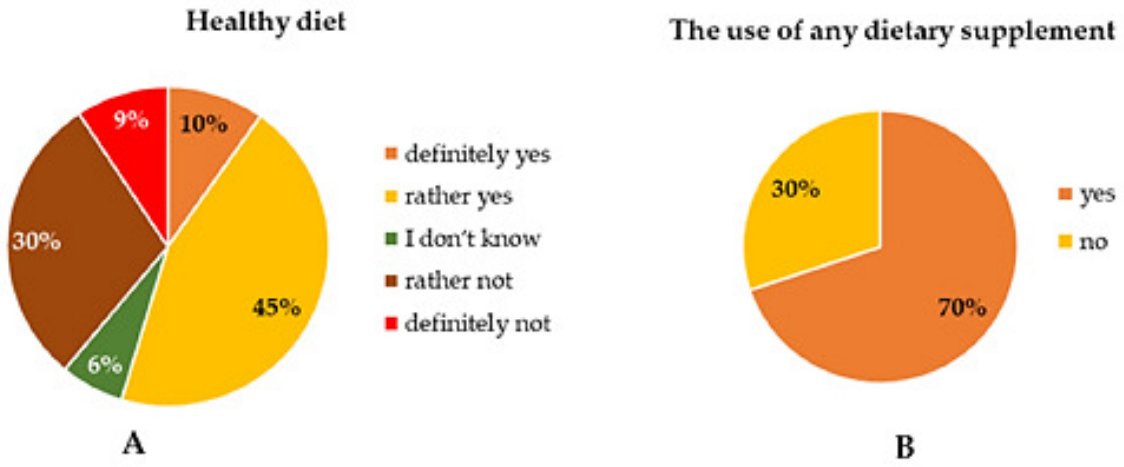


Figure 2. Declared type of diet (A), the overall use of my dietary supplements in the group of respondents (B).

Source: (Dickinson et al., 2014).

This situation has far-reaching consequences for all interested parties representing the supply-side of the exchange (including manufacturers, distributors, subcontractors, state treasury) and consumers - representatives of the demand-side. Unfortunately, study results show that the consequences are not equivalent for each of the aforementioned market exchange groups (Bergins, Kreft, 2014; Katz, Meller, 2014; Price, 2005; Hollenstein, 1994).

Enterprises and institutions representing the supply-side of the exchange mainly assess the competitiveness and attractiveness of the food supplements sector. The assessment usually encompasses the viewpoints of potential buyers, the competition and suppliers (Porter, 1979). It is also conducted based on an analysis of key indicators that cover financial, technical and technological, social and cultural, legal and political criteria and international conditions, among others (Adamik, Matejun, 2012). In great simplicity, the interested parties invest in the given sector when they see the prospect of income.

The main issue is the return on investment, profits earned or the contribution to the state budget in tax revenues from the sale of food supplements. The rapidly growing global food supplements market allows for the statement that the food supplements sector is (VERY) beneficial to entities representing the supply-side of the exchange (Mordor Intelligence Report, 2023; McKinsey, 2013). At this point, it is necessary to ask the question whether the food supplements market is equally beneficial to individual consumers. When analysing the scientific sources in taking into account the viewpoint of entities representing the demand-side of the exchange – mainly individual consumers – it turns out that the assessment of the results of food supplements consumption is no longer as clear (Hys, 2020; Watson et al., 2011). The advantages of using food supplements mainly include the fact that are the main concentrated source of vitamins or mineral components (Directive 2002/46/EC). They allow people with shortages to supplement them. Nevertheless, the consumption of food supplements also involves threats (Fassier et al., 2019). The aim of this paper is to identify the threats resulting from the use of food supplements by individual consumers. An essential part of this paper is devoted to this issue.

2. Matodology

The aim of this paper is to identify the potential threats resulting from the use of food supplements. At the same time, the authors' attention will be focused on the viewpoint of the demand-side, i.e. individual consumers. Literature analysis is the primary element of the issue recognition procedure. The literature review was performed according to the Hart five-element concept using the following stages: data identification and collection (1), data assessment – verification (2), bibliometric analysis (3), visualisation (4) as well as interpretation and description of study results (5) (Hart, 2018). The selection process is presented in Figure 3.

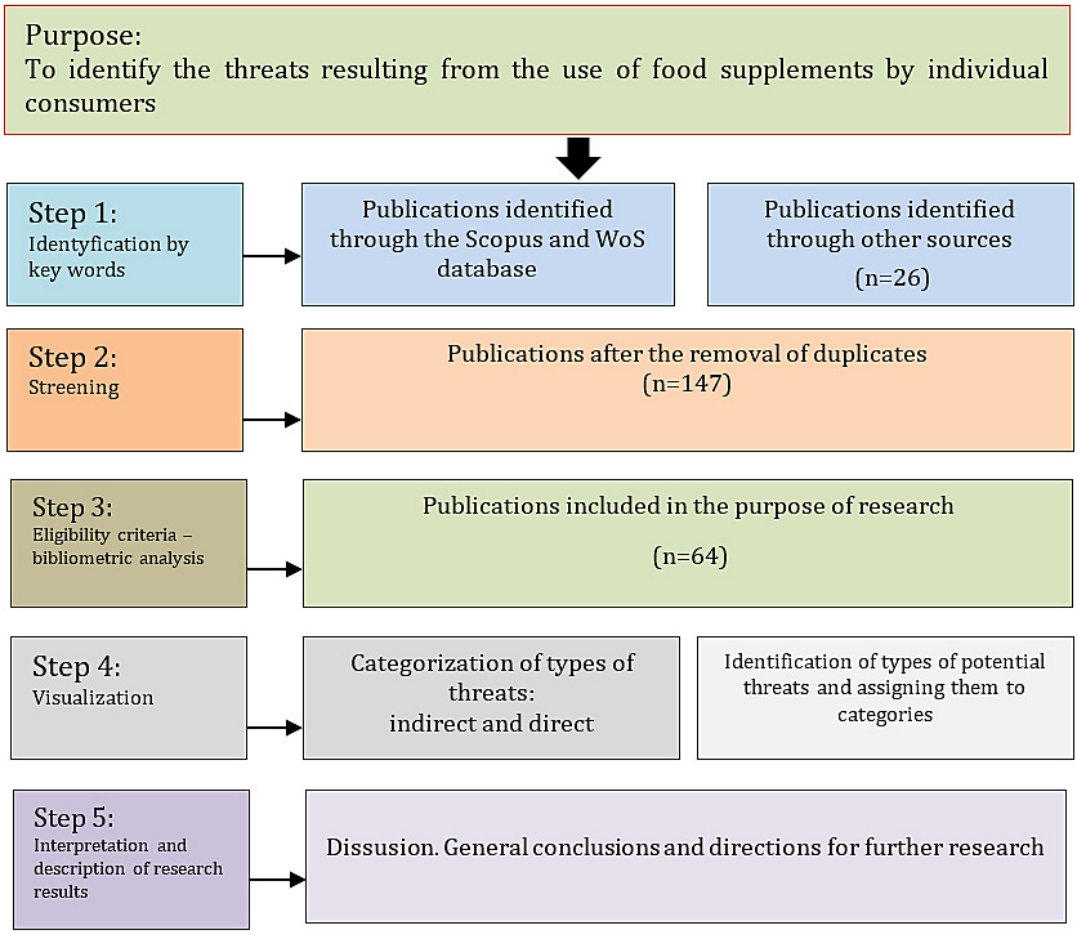


Figure 3. Literature review procedure.

Source: own study.

The identification of threats resulting from the use of food supplements by individual consumers mainly involved a review of electronic databases, such as WoS and Scopus. The publications subject to analysis were selected using keywords, such as: food supplements and potential threats. The analysis covered all publications containing the keywords. Related publications were published in 2002-2023 and 2018 for both the Scopus and WoS databases. The titles and abstracts of the publications were reviewed and selected prior to the analysis of full texts to determine their eligibility. The preliminary search encompassed the identification of publications for the WoS – 1, and for Scopus – 121. Due to the objective of the study, the literature analysis was also expanded with an analysis of reports and other thematic sources published in English and Polish. The scope of analysis was determined in the procedure as studying other thematic sources (n = 26). After combining the results, the returned database records and other sources, and removal of duplicates, a total of 147 publications remained for full text analysis. The full texts of publications were downloaded and reviewed in terms of eligibility, thereby leaving 64 texts eligible for review.

In addition, it is necessary to note that scientific databases contain publications on food supplements that are scattered in over a dozen different thematic fields (including agricultural and biological sciences, medicine, biochemistry, genetics and molecular biology, pharmacology, toxicology and pharmaceutics, food science technology, pharmacology pharmacy, biochemistry molecular biology, nutrition dietetics, etc.). The number of publications from specific fields ranges from over a dozen to single publications. This makes it impossible to point to a specific subject area at this moment. The studies are conducted randomly for single specific issues.

3. Results

Food supplements is a general name of foodstuffs, the main purpose of which is to supplement normal, i.e. balanced human diet. It is worth noting that food supplements consumption is intended to ensure nutrition or other physiological effect according to the concept of legislative bodies. This is derived from further regulating entries in which food supplements are defined as a concentrated source of vitamins, mineral components or other substances that enable achieving the assumed effect (Directive 2002/46/EC).

In these terms, food supplement undoubtedly have a very important function. At the same time, researchers have been raising the issue of potential threats resulting from the consumption of food supplements in various dimensions for over 20 years (Palmer et al., 2003). The conducted studies allowed for the identification of two **groups of potential threats**, i.e. – **indirect and direct**. The indirect threats concern the ingredients, quality of raw materials, manufacturing conditions, OHS rules and food supplements' manufacturing ethics. On the other hand, indirect threats concern the effects of using food supplements that affect the health of individual customers.

3.1. Indirect threats resulting from food supplements consumption

The literature review allowed for the identification of the following indirect threats for individual consumers of food supplements (Figure 4):

- metal poisoning, including heavy metals in ingredients of food supplements,
- contamination of food with residues from food supplements used (toxicity) – as a result of abusing food supplements in poultry and fish feeds,
- contamination of food supplements with undeclared presence of anabolic and androgenic steroids, pesticides used to combat insects and plant diseases (vegetable raw materials in specific food supplements), mycotoxins or
- falsification of food supplement ingredients, using cheaper substitutes,

- negligence or intentional omission of important markings on labels (ingredients, among others),
- common and persuasive marketing tools,
- no established state supervisory bodies or ineffective food supplement monitoring systems, malpractice reporting systems, quality control systems.

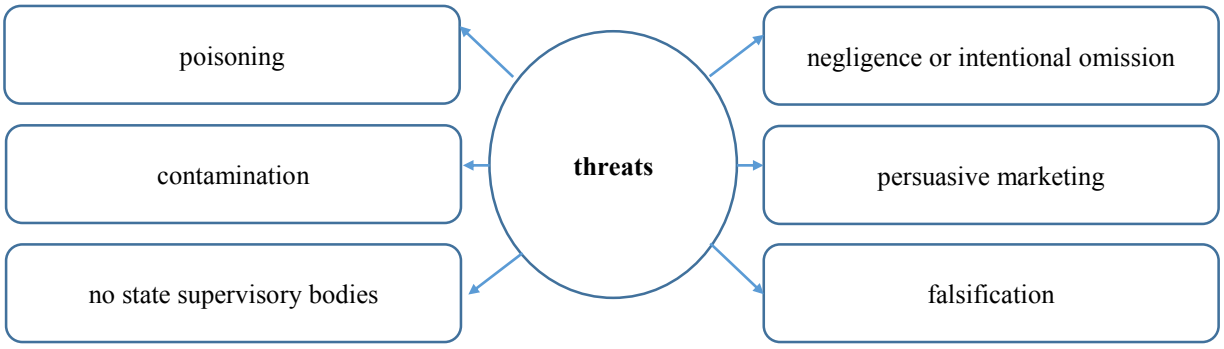


Figure 4. Food supplements consumption – indirect threats.

Source: own study.

In their studies, Brodziak-Dopierała, Fischer, Chrzanowska and Ahnert referred to the threat of heavy metal toxicity in food supplements. Due to the increasing environmental contamination, they conducted studies on the raw materials used in the production of vegetable oils, shark liver oils and cod liver oils in terms of contamination with toxic substances, including mercury (Hg). This results from the fact that vegetable and fish oils are commonly used as a primary ingredient of food supplements (mainly in liquid form) due to the active ingredient's bioavailability. The objective of the conducted studies was to aid the determination of the studied preparations' contamination with mercury and the related potential threats to human health (Brodziak-Dopierała, et al., 2023).

Other studies concerning the metal toxicity as result of copper and zinc accumulation in fish were conducted by Wand et al. (Wang et al., 2020). The threats of excessive loading of human food with food supplements resulting from "overfeeding" animals with enriched feeds were also a subject of scientific studies. The study of broiler chicken – a source of meat for consumers – in terms of overuse of food supplements in poultry farming identified a potential threat to meat safety and to consumer health. Wu et al. studied the role of a food supplement – lauric acid – used in poultry feeds and the potential threats resulting from its overuse (Wu et al., 2021). Broiler chickens were also studied in terms of vitamin C supplementation and its impact on meat quality (Gan et al., 2020).

On the other hand, Islam et al. conducted studies on feeds enriched with growth stimulants, given to broiler chickens. Studies were conducted in order to analyse the quality parameters of meat eaten by consumers, that could have potentially involved accumulation of residues, e.g. dexamethasone (DEX) (Islam et al., 2022). Contamination of food supplements with various substances is another category of threats for consumption. Holubová et al. conducted

studies concerning the undeclared presence of various substances, including anabolic and androgenic steroids in commercial supplements. The specific issue was the potential threat for all athletes who used those supplements. The so-called unintentional use of performance-enhancing drugs is also a common phenomenon (Holubová et al., 2021; Mathews, 2018).

Moreover, Liu et al. conducted studies on the contamination with pesticides used to combat insects and diseases in terms of the basic ingredient of spices and herbal treatment, i.e. Glycyrrhiza uralensis (Liu et al., 2020). Kampf et al. dealt with a different type of contamination in their research. They studied the contamination of foods and feeds, especially of food supplements, with pyrrolizidine alkaloids, among others (Kempf et al., 2010). Xu et al. analysed the issue of using natural food supplements which, on one hand, demonstrate the potential to reduce muscle atrophy and improve their performance in terms of the population ageing processes (the so-called Sarcopenia-based ageing syndrome) (Marsman et al., 2018).

On the other hand, the contamination of raw materials used in food supplements and establishment of a mechanism allowing for the regulation of tea pigments in muscle function were also important (Xu et al., 2022). Scientists are also pointing to the threat related to the presence of mycotoxins, i.e. citrinin (CTN vs Monascus purpureus), used as ingredients in food supplements, due to their potential of reducing cholesterol levels (Liu et al., 2005). It is a significant issue and researchers are presenting ample evidence for its existence (Benatrehina et al., 2018; Palmer, Rao, 1999). The falsification of food supplements is also a very important issue. Xin et al. demonstrated that it mainly applies to traditional herbal medicinal products (THMP). In their research, they pointed out the threats to consumer health, resulting from the consumption of fake food supplements that do not meet the quality standards (Xin et al., 2018).

Dishonest manufacturers use substitutes with reduced quality parameters, fillers or other ingredients with untested effects on the human body, place incomplete description of ingredients on packaging or don't include contraindications for using the supplements. These entries are often purposefully omitted by dishonest manufacturers, traders, etc. (Fransson, 2021; Ko, 1998). In general, such actions can potentially pose a great risk to consumer health and life. Moreover, the issue can be viewed also in terms of the toxicity of food supplements (Pillans, 1995).

Furthermore, it is necessary to point to another potential threat related to using formal and legal rules by dishonest manufacturers to market deficient food supplements. Researchers have noted gaps in the notification procedure that can be used by dishonest food supplement manufacturers. It must be emphasised that the current formal and legal rules have a limited range and are used with various severity in different countries. Literature also points out the potential threat resulting from no established state supervisory bodies or ineffective food supplement monitoring systems, malpractice reporting systems and quality control systems. A good, but insufficient, practice is to introduce community-level regulations (EU) or regulations in other countries (e.g. Rapid Alert System for Food and Feed – RASFF;

FDA registers; CFSAN Adverse Event Reporting System, ANSES is the French Agency for Food, Environmental and Occupational Health & Safety - EudraVigilance; Nutrivigilance).

Nevertheless, further findings show that excessively liberal rules of law require immediate clarification and expansion in terms of tightening the notification procedures, effective supervision during the registration of food supplements for marketing. It is also possible to mention the need to limit the manufacturers' excessive freedom concerning the declared ingredients of food supplements, complete label descriptions, information on interactions, contraindications or adverse effects (Hys et al., 2023; Wróbel et al., 2023; Supreme Audit Office Report, 2022; Petkova-Gueorguieva et al., 2019; Hanekamp, Bast, 2007; Coppens et al., 2006; Dvorkin, Gardiner, 2003).

The so-called information noise is the last, but not the least important threat for consumers. Consumers are being constantly manipulated by the market in the form of various incentives concerning the apparent need to consume food supplements. Marketing procedures are used commonly and the manufacturers use professional persuasion tools, thereby making them very effective. Consumers feel forced to consume food supplements, because "they have a preventive effect and allow for near immortality" (Manuti et al., 2023; Motoki et al., 2022; Hys et al., 2022; Hua et al., 2021; Campbell et al., 2021; Fernández, 2020; Menger-Ogle et al., 2018).

3.2. Direct threats resulting from food supplements consumptions

The second type of threats resulting from the use of food supplements by individual consumers are direct threats. In literature, researchers refer to the following threats (Figure 5):

- effect on the human body, including the respiratory system, of the consumption of food supplements administered as probiotics and vitamins,
- inappropriate manner of food supplements' consumption – excessive or insufficient supplementation,
- interaction between food supplements (or their ingredients) and other agents or the occurrence of adverse effects for the human body,
- irrational reasons for the consumption of specific food supplements – freedom in selecting different types of food supplements,
- the polypharmacy phenomenon – interaction with drugs,
- occurrence of alterations in the body's functioning or structure,
- insufficient consumer knowledge about food supplements and equating them with drugs.

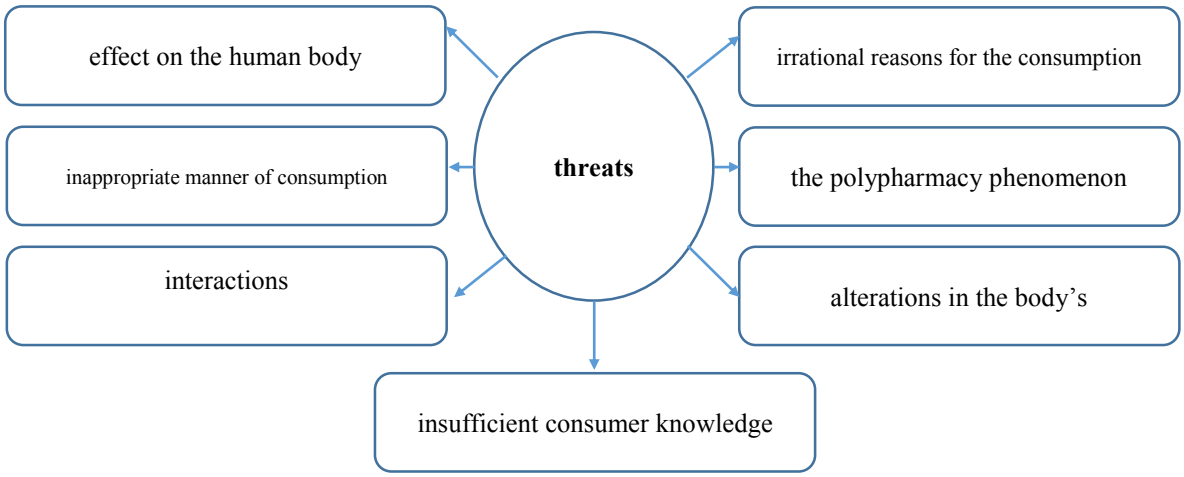


Figure 5. Food supplements consumption – direct threats.

Source: own study.

Huang et al. performed a review of clinical features for respiratory tract diseases, such as allergic rhinitis and allergic asthma, in terms of probiotics in prevention and treatment of changes in intestinal microflora and in terms of their activity. Huang et al. tested probiotics (food supplements) that modulate both congenital and acquired inflammatory reactions. These probiotics are often used to provide health benefits in gastro-intestinal disorders.

However, the main issue is their causality, because probiotics can be used as immuno-modulators and activators of the patient's defence response pathways. Consequently, oral probiotics can modulate the immune response in the respiratory tract. Hence, the quality of raw materials used in food supplements and their ingredients are a fundamental issue, because they have a real impact on the functioning of the human body (Huang et al., 2022).

On the other hand, Martineau et al. studied vitamin D supplementation in terms of its potential to prevent acute respiratory tract infections (Martineau et al., 2019). Multi-dimensional studies are being conducted on vitamin D supplementation (Ofoedu et al., 2021; Jadhav et al., 2020; Del Mondo, 2020).

Literature includes papers that point to another type of threats resulting from inadequate consumption of food supplements. Consumer threats may arise from the use of supplements in discordance with the recommendations – the consumer can overdose food supplements. Both deficiency and excess are potentially dangerous for consumers (Andrade et al., 2018; Kerrigan, Lindsey, 2005). Another issue is the consumers' freedom to use food supplements. Consumers select food supplements based on various factors, often irrational ones (due to marketing activity, e.g. consumers heard about a product in ads, friends recommended the given supplement, etc.) (Supreme Audit Office Report, 2023; Hys et al., 2022; Temple, 2012; Merlin, 2008; Dennehy, 2005). Consumers also admit that they usually don't notify their physicians about taking food supplements (Zalewski, 2020; Kowalczyk et al., 2017 Rogovik et al., 2010; Izzo, Ernst, 2001). This attitude unfortunately multiplies the risk of adverse interactions between active substances contained in food supplements and in medicine (Simundic et al., 2018).

Interactions may cause a food supplement to limit the body's ability to uptake a drug, reduce or enhance the drug's healing effect is shown in Figure 6 (Ikuta et al., 2019).

Also other cases are described in the literature **(**DeRemer, 2014; Avoid these…, 2013; Bojarowicz, Dźwigulska, 2012; Pyrzanowska et al., 2006)**.** The threat is related to the polypharmacy phenomenon. The phenomenon involves an inadequate multi-drug therapy. Taking multiple substances (food supplements and drugs) at the same time may cause interactions that have adverse effects for the human body, posing a threat to the patient's life and health (Woroń et al., 2016; Hrnciarikova et al., 2012; Timbo et al., 2006; Péter et al., 2017).

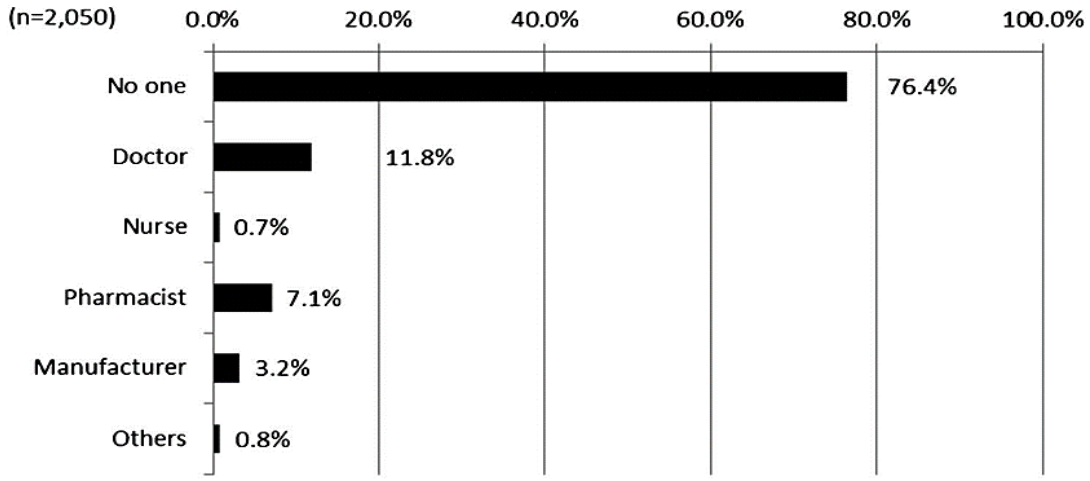


Figure 6. Who Do You Consult about the Combined Use of Medicine and Supplements?
Source: (Ikuta et al., 2019).

Threats related to interactions between food supplements (or their ingredients) and other agents (including drugs) or the occurrence of adverse effects for the human body, Many food supplements, including those used by athletes, contains compounds that enhance vascularisation, shorten muscle regeneration and reduce the mean arterial blood pressure. Catrambone and Dawson demonstrated that this is a potential threat to the health and life of military aircraft pilots (at G loads) (Catrambone, Dawson, 2013; Knapik et al., 2022).

Scientists also noticed that the consumption of food supplements can give rise to a different threat – it can damage DNA when using food supplements containing chromium picolinate (Hepburn, Vincent, 2002). Finally, attention should be drawn to the limited consumer knowledge about the nature, purpose and ingredients of food supplements, and their manufacturing method, quality of raw materials, ethics, legal regulations or actions taken by entities representing the supply-side of the exchange.

Due to active marketing campaigns, food supplements in different forms (i.e. capsules, pills, tablets, powder sachets, drinking ampoules, bottles with droppers, liquids and powders intended for consumption in small, portioned unit quantities) are equated with over-the-counter drugs (OTC), or at least with substances with medicinal properties, which is obviously not true (Hys, 2018).

4. Discussion

As demonstrated, the number and types of potential threats resulting from the use of food supplements are vast and immensely important, because they can affect the health of consumers and the entire population. The results of conducted studies allow for the statement that publications devoted to threats related to the use of food supplements are diverse in terms of their topics. Hence, they concern many somewhat random incidents. Nevertheless, it is possible to conclude that the threats related to the use of food supplements are common, real and multi-dimensional.

Therefore, it is certainly necessary to conduct broad studies to identify and eliminate the threats (Gardiner et al., 2008). Due to the mass and social nature of information on the "universal beneficial effects" of food supplements, consumers are almost forced internally to use them. It is worth noting that the usual media message on the multifaceted stimulation of the body caused by the consumption of food supplements is so evocative and malleable that consumers feel a real need to use them. Unfortunately, such actions give rise to many negative consequences (Rautiainen et al., 2014).

As a general rule, food supplements are recommended to people with deficiencies in or higher demand for vitamins and nutrients (i.e. people during recovery, pregnant women, athletes, elderly people) (Rasmussen et al., 2005; Kloosterman et al., 2007). Therefore, food supplements are not recommended to all consumers. On the contrary, they are only recommended to some consumer groups and usually at a specific time or in certain conditions. A balanced diet should be sufficient to supply the body with the adequate quantity of vitamins and nutrients with every-day meals (Biesalski et al., 2003; Richardson, 2014).

There are principally three methods of providing the body with the necessary nutrients. These include: a balanced diet, enriched foods and food supplements. The fundamental method of body nutrition involves using a balanced and reasonable diet that takes into account the given body's needs. In situations requiring the supplementation of deficiencies (resulting from, e.g. past illnesses, etc.), consumers can use enriched foods and food supplements to address vitamin and nutrient deficiencies. This means that food products (both enriched foods and food supplements) are only products that supplement a balanced diet and in no way can they replace it. Meanwhile, the current common approach is to promote a message stating that "the consumption of food supplements is a way of life for modern populations". However, many researchers point out that such a message is a classic marketing tool (Hys et al., 2022; Reinert et al., 2007; De Jong et al., 2003; Ishihara et al., 2003; Hulshof et al., 1991). It is used to create consumer needs and arouse widespread desire for supplements and their consumption (Kotler, 1967). This activity is typical for supply-side behaviours and is economically justified. However, from the demand-side's viewpoint, mindless subordination to information noise and

making life dependent on "market expectations" is extremely irresponsible. It could even be considered as bordering on madness (Flynn et al., 2003).

The volume, variety and simultaneity of the consumption of food supplements is growing dynamically. The approach to food supplements' consumption is therefore a common threat to the health and lives of consumers and entire populations. Consumers make reckless decisions to consume food supplements without making a cognitive effort. A classic example concerns the decision to supplement vitamin D. The fundamental question is – do consumers and how many of them test their vitamin D deficiency before they start supplementing it? The answer seems to be obvious. This mechanism can be repeated for nearly all consumer decisions regarding supplementation.

Another issue is the consumers' awareness of the effects of food supplements on the human body. As stated by Chiba et al., consumers usually think that food supplements are completely safe and neutral when used simultaneously with drug therapies (Chiba et al., 2015). As noted, consumers erroneously equate food supplements with OTC drugs. What is even more irrational, consumers expect food supplements to have a healing effect. Literature presents numerous examples that contradict this manner of thinking. It is a complex issue that concerns many aspects. These include the polypharmacy phenomenon, the consumers' ignorance about the effects of specific ingredients on their body, their impact on the results of the body's laboratory tests (data corruption, medical misdiagnosis, etc.), **limited drug absorption by the body, disruption of the healing effects of drugs taken,** or the lack of comprehensive knowledge on the ingredients of food supplements (e.g. as result of dishonest manufacturer practices). Another aspect that must also be studied in more detail is the method of determining the acceptable standards for the consumption of specific ingredients, depending on the consumers' individual factors (demographic, social and cultural, economic determinants, etc.). It must be noted that different countries have different standards for the consumption of the same substances and that these standards change over time. Another aspect is the marketing or prohibition of using certain ingredients. A good example is melatonin, which in France is treated as a food supplement at a dose of up to 2 mg, while in Poland – at a dose of up to 1 mg, and cannot be added to food supplements in Czechia (Van Regnault et al., 2021). Such a situation is not incidental and it must be kept in mind. It is clear that the consumption of food supplements involves a great deal of risk. The threats identified are widespread, real and important for the entire population. It is therefore recommended to make reasonable decisions about the consumption of food supplements based on knowledge. It is also worth thinking about life priorities – is anything else important if a human is not healthy? The argument is about having a multifaceted discussion about this topic.

Continuing the discussion on the consumption of food supplements, let the following dilemma be addressed: **Will food supplement consumption cause a consumer to become a millionaire or go broke?**

The attempt to provide an answer is as follows:

- Adopted assumption 1: A consumer spent their entire wealth on food supplements, but they are indeed a remedy to all deficiencies and assure a long and healthy life, resulting in... immortality. Then the answer is: the consumer is a millionaire.
- Adopted assumption 2: A consumer spent their entire wealth on food supplements, but they are ineffective and only give an illusion of a long and healthy life, resulting in... (early) mortality. Then the answer is: the consumer is broke. There are obviously many variants of a hypothetical situation that can be addressed. However, the authors' objective is to draw attention to the universality, timeliness and validity of the addressed notion. At the same time, it is an invitation for scientists to conduct a multifaceted analysis of the issue.

5. Conclusions

Worldwide research on the effects of the consumption of food supplements is fragmented. As a rule, reports are focused on conveying the benefits of food supplements through their beneficial effects on the human body. At the same time, scientists **rarely address the issue of potential threats resulting from the consumption** of food supplements. As a result, there is currently no comprehensive way to consider the effects of human consumption of food supplements.

- In this study, the authors attempted to identify the potential threats resulting from the consumption of food supplements by individual customers. The conducted studies allow for the conclusion that the spectrum of threats related to the consumption of food supplements is enormous. The following categories of threats were identified: indirect and direct. Many specific characteristics were assigned to each category, all of them important and having real effects on the health of individual consumers and entire populations.
- As a result of the above, it is possible to conclude that both indirect and direct threats are real and occur commonly. It is expected that the scale of the issue will grow due to the dynamically growing global market of food supplements.
- At the same time, it is very worrying that no comprehensive research is being conducted on this issue. The published papers usually concern the following areas: agricultural and biological sciences, medicine, biochemistry, genetics and molecular, biology, pharmacology, toxicology and pharmaceutics, environmental science, immunology and microbiology, nursing, chemistry. There is also a small number of thematic publications on management, psychology, quality, manufacturing or ethics.

- The dispersion and fragmentation of data prevents the study of the scale of threats caused by the consumption of food supplements by individual customers or entire populations.
- In summary, it is considered necessary to carefully lean into the identified potential threats resulting from the consumption of food supplements. Further research should be carried out to gain comprehensive knowledge on the scale of the threats and to establish monitoring systems applicable to the quality of food supplements, as well as educational systems for societies to ensure that food supplements are used as intended – only for the purpose of supplementing identified deficiencies in the body.

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ASSESSMENT OF ECOSYSTEM SERVICE POTENTIAL IN POST-MINING AREAS FOR SUSTAINABLE MANAGEMENT

Beata KOŃCZAK[1*], Adam HAMERLA[2]

[1] Central Mining Institute, Department of Water Protection, Katowice, Poland; bkonczak@gig.eu, ORCID: 0000-0003-4398-7653
[2] Central Mining Institute, Department of Water Protection, Katowice, Poland; ahamerla@gig.eu, ORCID: 0000-0002-9129-2621
* Correspondence author

Purpose: The purpose of this study is to develop and apply an integrated algorithm for evaluating the ecosystem service potential of post-mining land and identifying the demand for such services in adjacent areas. The research addresses the growing need for sustainable spatial management of degraded industrial areas and aims to support evidence-based decision-making in post-mining land redevelopment.
Design/methodology/approach: The assessment was conducted across four distinct post-mining sites, considering variables such as land cover composition, landscape heterogeneity, presence of hydrological features, and anthropogenic infrastructure. The proposed methodology facilitates the identification of optimal land-use strategies, supporting sustainable spatial planning and redevelopment of degraded post-industrial sites.
Findings: The results demonstrate that applying ecosystem service-based valorisation enhances decision-making processes and aligns land reclamation with broader socio-economic and environmental objectives. The results indicate that the applied algorithm makes it possible to identify effective development directions for a studied post-mining area as well as support the decision-making process in the spatial management of sites that have lost their economic functions.
Practical implications: The value of the work lies in offering a replicable tool for planners and decision-makers seeking to align land reclamation with ecological and societal benefits. It contributes to bridging the gap between environmental science and strategic land-use management.
Originality/value: This paper presents a novel, integrated method for assessing post-mining land in terms of its potential to provide ecosystem services—a perspective that remains underexplored in current literature.
Keywords: spatial planning, environmental valorisation, land attractiveness, land cover analysis.
Category of the paper: Research paper.

1. Introduction

1.1. The Impact of Environmental Degradation on Ecosystem Service Provision

Sustainable land management plays a pivotal role in optimizing the environment's potential to deliver essential goods and services to society (Elmqvist et al., 2015; Ramirez, 2019). The expansion of anthropogenically transformed landscapes alters both the quantity and type of ecosystem services provided and modifies societal demands on the environment. For instance, areas with high levels of surface sealing intensify the need for rainwater and snowmelt retention systems. Similarly, high population densities elevate the demand for accessible recreational green spaces. Integrating ecosystem service considerations into development strategies is vital to enhancing human well-being and supporting sustainable economic growth (Ahirwal, Pandey, 2021).

Extractive activity leads to negative and often irreversible damage to ecosystems, both during coal deposit exploration as well as after mining is concluded (Neves et al., 2016; Rusche, 2019). Sanchez et al. (2014) state that aspects related to environmental protection and a lasting positive legacy for society as regards mine closure should be factored in at every stage of a mine's life cycle. This can be made possible with the engagement of broad groups of stakeholders across a mine's entire life cycle and the constant assessment of the influence that the mining activity exerts on the environment and society.

Numerous reports can be found in literature as regards the negative impact of extractive activity on: aquatic and terrestrial ecosystems (Mercado-Garcia et al., 2018; Beck et al., 2020), woodland areas (Obeng et al., 2019; Sonter et al., 2017; Zipper et al., 2011), microbial ecosystems (Orcutt et al., 2020; Tost et al., 2020) and biodiversity (Prach, Tolvanen, 2016).

The progressing growth of the economy and population leads to an increase in the demand for ecosystem services and the need for the sustainable management of post-industrial and post-mining land to restore its functions related to ecosystem services (Rosa et al., 2019).

1.2. Restoration Approaches

Ahirwal et al. (2021) state that mining activity leads to ecosystem service depletion through deforestation, topsoil and overburden displacement and the removal of significant bulks of waste and earth. However, they indicate that the appropriate reclamation measures, particularly planting plants resistant to climate change and stress conditions that are also native species, may enable the restoration of the ecosystem condition to a degree where it would be capable of providing ecosystem services and meeting the goals of international policies such as the UN Sustainable Development Goals.

Post-mining land reclamation towards reforestation may improve the resistance to climate change and alleviate its impact at a regional scale, while reclamation towards arable land and pastures may have a positive influence on local food production and the use of bioenergy (Larondelle, Haase, 2012).

On the other hand, Gwenzi (2021) reports the necessity to develop new guidelines for post-mining land reclamation. Currently the sole determinant for assessing the potential for restoring post-mining land to a useful state are the results of soil quality testing (e.g., pH, organic carbon content in the soil) (Bandyopadhyay et al., 2020; Agus et al., 2016). Post-mining land restoration should be performed using the results of tests conducted by means of innovative testing tools such as drones, laser cameras, genomics, big data analytics (Gwenzi, 2021) or satellite image analyses (McKenna et al., 2020). Such innovative tools can help unravel the complex relationships between biotic and abiotic components as well as ecosystem functions and services, which are currently difficult to investigate by means of conventional techniques.

1.3. Ecosystem Service Valuation

However, there are few literature reports concerning the transformation of post-mining areas in a manner that would enable benefiting from the ecosystem services provided by them (Boldy et al., 2021). Similarly, Boldy et al. (2021) report a lack of methodological cohesion in assessments of the post-mining land potential for providing ecosystem services.

Addressing this gap, the present study introduces a comprehensive algorithm for assessing ecosystem service potential and evaluating demand in surrounding areas. This approach leverages cutting-edge analytical tools to inform strategic planning and support evidence-based spatial management of post-industrial land.

2. Materials and methods

2.1. Characteristics of the study areas

The studies were conducted for 4 post-mining areas differing in the type of land cover as well as the presence of utilities and buildings. All the analysed areas were located in the Silesian Voivodeship in Poland. This region of Poland exhibits an industrial character based on traditional branches of manufacturing. It is currently undergoing an industrial restructuring process involving the total or partial decommissioning of mines, obsolete steelworks and associated processing plants. The closure of these sites leads to the generation of post-industrial and post-mining areas that require reclamation. The sites are characterised below:

Site 1 – "Borowa 2" waste dump located in Ruda Śląska, Poland

The former waste dump of the Bielszowice mine. The area is covered with dense vegetation and is located in the vicinity of green areas – woodland and agricultural – in the Kłodnica river valley. The site is currently used for recreational purposes. It exhibits significant height differences. It is undeveloped and no buildings or waste can be found there. The site has access to a public road.

Site 2 – Site of the decommissioned Rozbark coal mine encompassing railway siding, Bytom, Poland

The site of the decommissioned Rozbark coal mine encompassing former railway siding, stockyards and primary plant infrastructure. The area is flat, developed and covered with vegetation. Historical structures (railway siding) can be found in a part of the site. There are no buildings or access to infrastructure in the remaining, greater part of the area. In its vicinity are industrial sites as well as residential and service infrastructure. It has access to a public road.

Site 3 – Reclaimed site of the Powstańców coal mine, Bytom, Poland

Flat area with a regular shape, undeveloped and covered with low-growing vegetation. It is located in the immediate vicinity of green woodland areas as well as industrial sites. From the north it borders a manufacturing plant, whereas its west and south borders are by the Segiet stream bed and the Szarlejka river bed. The site has access to a public road.

Site 4 – Waste dump and transport infrastructure of the Michał coal mine, Siemianowice Śląskie, Poland

Settling ponds partially filled with water can be found at the top of the waste dump. Dirt coverage, with dense uncontrolled vegetation in the southern part. Visible unpaved traffic routes. Service, residential and recreational infrastructure can be found in the vicinity of the site. It has access to a public road.

Figure 1 displays images taken with a drone to present the varied structure of the land cover.

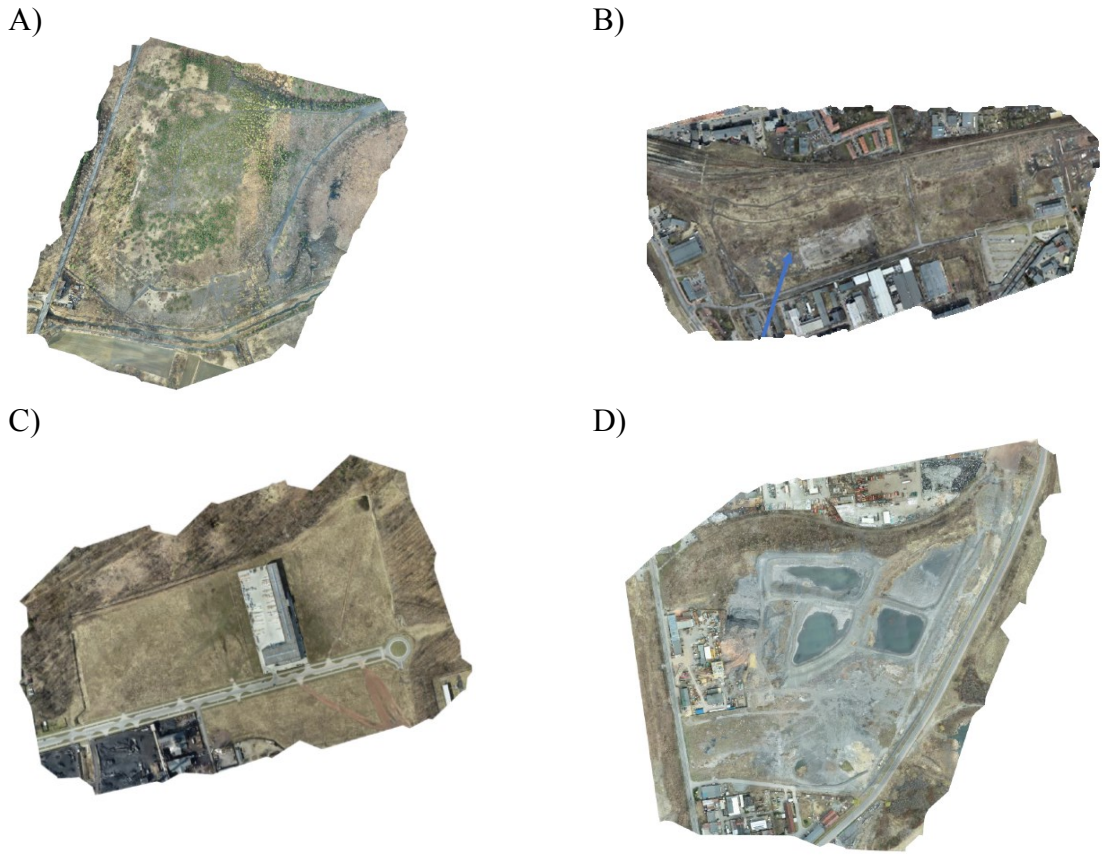


Figure 1. Analysed areas A) Site 1 – Borowa 2 waste dump in Ruda Śląska, Poland; B) Site 2 – Site of the decommissioned Rozbark coal mine encompassing railway siding, Bytom, Poland; C) Site 3 – Reclaimed site of the Powstańców coal mine, Bytom, Poland; D) Site 4 – Waste dump and transport infrastructure of the Michał coal mine, Siemianowice Śląskie, Poland.

Source: GIG-PIB.

The analyses were conducted for the 4 post-mining areas as well as for their vicinity within a radius of 1 km from the defined site borders and municipalities where the sites are located.

2.2. Assessment of the demand for areas with high recreational attractiveness at the municipality scale

In order to assess the demand for areas with high recreational attractiveness in a municipality that contains a post-mining area, the recreational attractiveness of the studied sites was analysed per the methodology proposed by Lupa (2016). This methodology was selected due to its proven effectiveness in evaluating recreational potential based on land cover, which directly influences the accessibility and perceived quality of natural areas.

The land cover type was defined based on the Corine Land Cover classification (Urban Atlas, 2018), which offers standardized, comparable, and spatially explicit data on land use across Europe.

The recreational attractiveness factor values (WAR_{LULC}) depending on the type of land cover are compiled in Table 1.

Table 1.
WAR_{LULC} values depending on the land cover type

Land type	Land description	Type per the Corine Land Cover classification	CLC type	WAR_{LULC}
Developed and urbanized anthropogenic land	Continuous urban fabric	Continuous urban fabric	111	37.12
	Discontinuous urban fabric	Discontinuous urban fabric	112	37.12
	Industrial or commercial units	Industrial or commercial units	121	37.12
	Controlled vegetation	Green urban areas	141	52.78
		Sport and leisure facilities	142	53.78
	Traffic infrastructure	Road and rail networks and associated land	122	37.12
	Mining grounds	Dump sites	132	37.12
		Mineral extraction sites	131	37.12
	Other developed land	Construction sites, Port areas, Airports	133, 123, 124	37.12
	Urbanised undeveloped land[1]	Several types, mean value		51.64
	Cemeteries	Green urban areas	141	52.78
Reclaimed land	Land transformed into woodland areas	Broad-leaved forest, Coniferous forest, Mixed forest	311, 312, 313	76.26
	Land transformed into agricultural areas	Non-irrigated arable land Permanently irrigated land	211, 212	47.47
		Complex cultivation patterns	242	48.65
		Land principally occupied by agriculture, with significant areas of natural vegetation	243	56.48
		Agro-forestry areas	244	47.47
		Pastures	231	45.71
		Annual crops associated with permanent crops	241	47.47
Agricultural land	Arable land	Non-irrigated arable land	211	47.47
		Permanently irrigated land	212	47.47
	Complex cultivation patterns[2]	Several types, mean value	242	48.65
	Land principally occupied by agriculture, with significant areas of natural vegetation[3]	Several types, mean value	243	56.48
	Orchards[4]	Several types, mean value		56.48
	Permanent meadows	Pastures	231	45.71
	Permanent pastures	Pastures	231	45.71
	Developed agricultural land	Discontinuous urban fabric	112	47.47
	Ground under orchards	Water bodies	512	73.23
	Ground under ditches	Water bodies	512	73.23

[1] Arithmetic mean for factors for arable land, pastures, moors and heathland, and built-up areas.
[2] Arithmetic mean for factors for arable land, pastures and controlled vegetation.
[3] Arithmetic mean for factors for arable land, pastures, forests, moors and heathland.
[4] Arithmetic mean for factors for arable land, pastures, forests, moors and heathland.

Cont. table 1.

Woodlands	Forests	Broad-leaved forest	311	76.26
		Coniferous forest	312	76.26
		Mixed forest	313	76.26
	Forests and shrubbery in transition[5]	Several types, mean value	324	60.99
	Moors and heathland	Moors and heathland	322	76.26
Tree-and shrub-covered land	Natural swards and pastures	Natural grassland	321	45.71
	Sclerophyllous vegetation	Sclerophyllous vegetation	323	45.71
	Dispersed vegetation	Sparsely vegetated areas Sparsely vegetated areas	333	45.71
Marshes	Inland marshes	Inland marshes	411	45.71
Water courses		Water courses	511	73.23
Water reservoirs		Water bodies	512	73.23
Ecological sites		Several types, mean value		65.07
Barren land	Naturogenic	Several types, mean value		65.07
	Anthropogenic	Construction sites	133	37.12

Source: Urban Atlas (2018).

These values reflect the assumed capacity of each land cover type to deliver recreational ecosystem services, based on empirical observations and prior valuation studies. For instance, forests and green urban areas are associated with higher attractiveness values due to their accessibility, biodiversity, and cooling effects in urban environments.

The weighted mean recreational attractiveness factor for the municipality was calculated using the following formula (1):

$$WAR_g = \frac{\sum_{i=1}^{n} S_i \cdot WAR_{LULC}}{\sum_{i=1}^{n} S_i} \quad (1)$$

where:

WAR_g – weighted mean recreational attractiveness factor for given land unit cover,

Si – surface area of an i-th site,

WAR_{LULC} – recreational attractiveness factor for an i-th site's land cover.

The classification of recreational attractiveness for each municipality was adopted as follows:

- A – High (61-80 pts).
- B – Medium (40-60 pts)
- C – Low (<39 pts)

The thresholds for classification were determined based on the natural distribution of WARg values obtained across multiple municipalities and on expert-based interpretation, ensuring consistency with previous studies (Lupa, 2016).

[5] Arithmetic mean for factors for pastures, forests, moors and heathland.

To assess demand, the inverse of the weighted mean recreational attractiveness factor was used, assuming that lower local attractiveness increases the demand for additional recreational spaces. The demand level was categorized as shown in Table 2, with threshold ranges derived from quartile-based distribution and sensitivity analysis conducted on a test sample of municipalities.

Table 2.
Classification of the demand for areas with high recreational attractiveness

Score	Demand class
1.2-1.4	Very high (1)
1.5-1.8	High (2)
1.9-2.2	Medium (3)
2.3-2.6	Low (4)

Source: GIG-PIB.

These classification thresholds were established to reflect meaningful differences in recreational demand levels across municipalities.

2.3. Assessment of the natural attractiveness of post-mining land

The natural attractiveness of post-mining land was assessed based on a modified version of the scoring method proposed by Jakiel (2015), which was adapted to the specifics of post-industrial terrains. The selected variables reflect key landscape features that influence the potential for recreational use and visual appeal, thus supporting the delivery of cultural ecosystem services.

Each component was selected based on its relevance to recreational and ecological potential:

- s1 – Lay of the land: Topographic variation enhances landscape diversity and is attractive for recreational use such as hiking.
- s2 – Presence of rock formations: Rocks provide aesthetic and geological interest.
- s3 – Type of land cover: Influences shade, biodiversity, and microclimate.
- s4 – Presence of water bodies: Water features are consistently valued in recreational landscapes.
- s5 – Landscape diversification: Heterogeneous landscapes are more attractive for users and better support biodiversity.
- s6 – Other anthropogenic objects: Certain features may either detract from (e.g., illegal dumping) or enhance (e.g., cultural heritage sites) recreational value.

Scoring for each criterion ranged from 0-3 points, calibrated based on expert knowledge, landscape guidelines, and previous empirical applications of the method. The criteria are presented in Table 3.

Table 3.
Scoring criteria depending on the analysed terrain attractiveness factor

Component	Group of criteria	Detailed criteria	Landscape evaluation criterion with assigned number of scoring points				
s1	Vertical variation and lay of the land	Average sloping	19-45°	9-18°	5-8°	<5°	
	Number of points		3 pts	2 pts	1 pt	0 pts	
s2	Visible rock formations	yes	3 pts				
s3	Types of land cover	cover %	1-25%	26-50%	51-75%	76-100%	
		Forests	1 pt	2 pts	3 pts	4 pts	
		Meadows	1 pt	2 pts	2 pts	1 pt	
		Arable land and orchards	1 pt	1 pt	0 pts	0 pts	
		Developed land	-1 pt	-2 pts	-3 pts	-4 pts	
s4	Presence of water bodies	Watercourse length	50-250 m			<300 m	
			1 pt			2 pts	
		Water reservoirs, rapids, waterfalls and karst springs (for their presence)	Per each water body				
			1 pt				
s5	Landscape diversification	Number of land cover types	1	2	3	4	
			0 pts	1 pt	2 pts	3 pts	
s6	Other anthropogenic objects (undeveloped)	Anthropogenic objects	Power lines	Asphalt roads	Antennas and other objects	Illegal rubbish dumps	Historical and cultural sites
			-1 pt	-1 pt	-2 pts	-2 pts	2 pts

Source: Jakiel, 2015.

The total score for each post-mining site determined its attractiveness class, according to the scale in Table 4. The threshold values (0-4, 5-9, 10-14, 15-18 points) reflect natural breaks in scoring and ensure differentiation between sites of varying recreational quality.

Table 4 presents the method of classifying land attractiveness depending on the number of obtained points.

Table 4.
Attractiveness classification for post-mining land and adjacent areas

Total number of points	Score	Attractiveness class
15-18	3	Very attractive
10-14	2	Attractive
5-9	1	Poorly attractive
0-4	0	Unattractive

Source: GIG-PIB.

The final post-mining land attractiveness assessment ranges within 0-3 pts. The higher the score, the more recreationally attractive the analysed post-mining area.

2.4. Assessment of the natural attractiveness of adjacent areas within a 1 km radius of the post-mining land

The natural attractiveness of areas adjacent to post-mining land was evaluated using a simplified approach based on two key components:

- Type of land cover (s3): Reflects general recreational and ecological value.
- Landscape diversification (s5): Indicates the variety of land uses, linked to environmental heterogeneity and user experience.

These variables were selected for their ability to provide a rapid assessment while maintaining consistency with the criteria used in the assessment of the post-mining land itself. The scoring and classification followed the same principles as described above, ensuring methodological coherence across spatial zones.

3. Results and discussion

3.1. Assessment of the demand for areas with high recreational attractiveness at the municipality scale

CLC 112 (discontinuous urban fabric) is the dominant type of land cover in all the analysed municipalities. In Siemianowice Śląskie, the other dominant types of land cover are arable and agricultural land (CLC 211) and industrial sites (CLC 121), which constitute 24% and 22% respectively of the municipality's surface area. Green urban areas (CLC 141 and CLC 142) constitute 7% and 11% respectively of the Siemianowice Śląskie surface area, whereas forests (CLC 311) amount only to 1%. The significant industrial and minor forest coverage distinguishes this municipality from the other analysed locations. Forests constitute 16% of the land cover in the Bytom municipality, and 12% in Ruda Śląska. Meanwhile industrial land in these municipalities constitutes 7% and 9% of the land cover for Ruda Śląska and Bytom respectively (Figure 2).

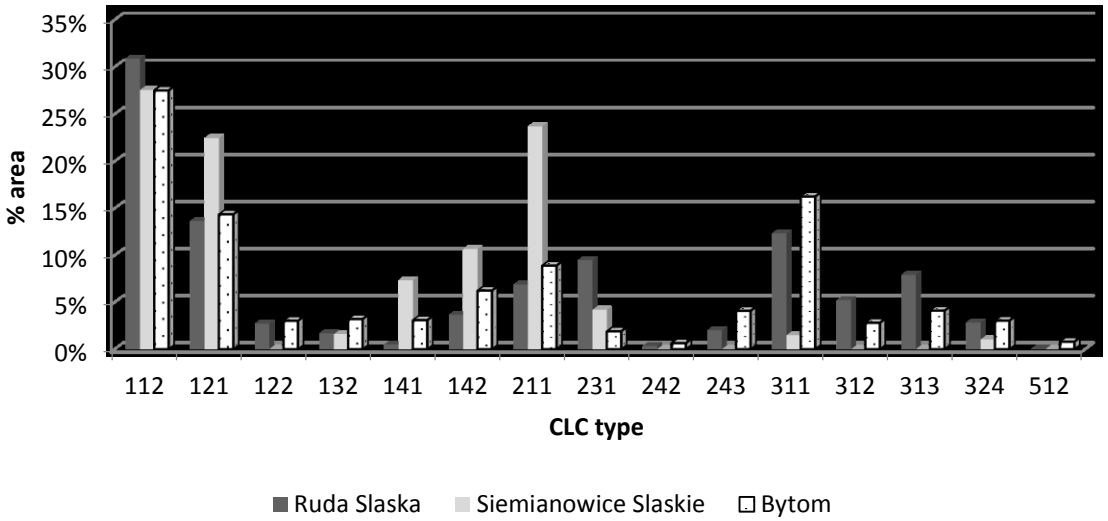


Figure 2. Land coverage for the municipalities of Ruda Śląska, Siemianowice Śląskie and Bytom with individual types of land cover per the Corine Land Cover (CLC) classification.

Source: GIG-PIB.

Further analysis demonstrated that the Siemianowice Śląskie municipality is characterised by the greatest demand for recreational areas among all the analysed locations (Table 5).

Table 5.
Analysis of the demand for recreational areas

Municipality	Surface area (ha)	WARg	1/WARg
Ruda Śląska	6947	50.60	2.0
Siemianowice Śląskie	7764	50.38	2.0
Bytom	2551	43.68	2.3

Source: GIG-PIB.

The coefficient of recreational area demand in Siemianowice Śląskie was 2.3, whereas in the remaining municipalities it was 2.0 (Table 5).

3.2. Natural attractiveness assessment

Table 6 presents the ecosystem service demand assessment analysis results and the potential for providing ecosystem services within a 1 km radius of the analysed municipalities.

The greatest recreational attractiveness factor of 2.7 was obtained for the vicinity of the post-mining site in Ruda Śląska, which results from the local presence of green areas, significant terrain mosaicity and the presence of a watercourse. Furthermore, Site 1 itself (Borowa II waste dump) is characterised by very high recreational attractiveness, and its attractiveness factor is 2.5.

The vicinity of Site 2 (Rozbark coal mine) is characterised by medium recreational attractiveness (attractiveness factor of 1.7), while the site itself exhibits high attractiveness (attractiveness factor of 1.5), which results primarily from the local presence of historical sites.

Site 3 (Powstańców coal mine) and Site 4 (Michał coal mine) are located in an area characterised by low recreational attractiveness (attractiveness factor of 0.3). Given its flatness, only partial coverage with low-growing vegetation, very low terrain mosaicity and lack of historical sites, Site 3 is characterised by the lowest attractiveness factor among all the analysed areas, amounting to 1.0. On the other hand, Site 4 exhibits high recreational attractiveness (1.5) due to the presence of settling ponds. The study results are presented in Table 6.

Table 6.
Recreational attractiveness assessment for post-mining land and its vicinity within a 1 km radius

Site	Site name	Municipality	Vicinity (r = 1km)	Site
1	Borowa II waste dump	Ruda Śląska	2.7	2.5
2	Site of the decommissioned Rozbark coal mine encompassing railway siding	Bytom	1.7	1.5
3	Reclaimed site of the Powstańców coal mine	Bytom	0.3	1.0
4	Waste dump and transport infrastructure of the Michał coal mine	Siemianowice Śląskie	0.3	1.5

Source: GIG-PIB.

The study results demonstrate that the applied algorithm for assessing the demand for recreational areas in municipalities as well as assessing the potential of post-mining land and its vicinity for providing ecosystem services constitutes an important tool for decision-making as regards determining the directions of transforming post-mining land into areas with useful properties.

4. Conclusions

This paper has introduced a comprehensive algorithm for assessing the ecosystem service potential of post-mining land and evaluating service demand in surrounding areas. The findings highlight that key determinants of service provision capacity include land cover type, landscape heterogeneity, proximity to water features, and the presence of cultural or historical landmarks. Importantly, The study revealed that the potential of post-mining land for providing ecosystem services does not always coincide with the recreational attractiveness of the adjacent areas, indicating the need for tailored, context-sensitive redevelopment strategies.

The study further demonstrates that municipalities differ significantly in their demand for the transformation of post-mining land transformation in a recreational direction, which should be taken into account in strategic planning. Access to green spaces and the continuity of green infrastructure emerged as crucial factors in guiding sustainable land-use decisions.

The results indicate that the applied algorithm can supports spatial management by enabling planners and decision-makers to identify optimal redevelopment paths for economically obsolete areas. It offers a practical, scalable framework for integrating ecosystem service

considerations into post-industrial land reclamation, contributing to both environmental resilience and socio-economic revitalization.

The following policy instruments and incentives can be helpful in integrating ecosystem services into spatial planning.

Incorporation of ecosystem service assessments into local and regional planning regulations,

- Financial incentives such as grants, tax reductions, or subsidies for projects that enhance ecosystem services, particularly those promoting green infrastructure, habitat restoration, and recreational development on post-mining lands.
- Development of cross-sectoral stakeholder platforms to foster collaboration between mining companies, local authorities, environmental organizations, and communities, ensuring participatory and transparent decision-making processes.

Implementing targeted policy measures and incentives will enable the effective achievement of sustainable development goals and improve the quality of life for local communities.

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EFFICIENCY INDICATORS OF PUBLIC TRANSPORT AS A TOOL SUPPORTING SMART CITY DEVELOPMENT

Agnieszka KOWALSKA-STYCZEŃ[1*], Karolina NOWAK[2]

[1] Silesian University of Technology, Faculty of Organization and Management;
agnieszka.kowalska-styczeń@polsl.pl, ORCID: 0000-0002-7404-9638
[2] Silesian University of Technology, Faculty of Organization and Management; kn304988@student.polsl.pl
* Correspondence author

Purpose: The purpose of this paper is to evaluate the efficiency of public transport systems as a supporting tool for smart city development. The study focuses on four cities within the Upper Silesian-Zagłębie Metropolis (Zabrze, Gliwice, Bytom, Ruda Śląska) and aims to identify strengths, weaknesses and spatial accessibility gaps in their transport networks using quantitative indicators and geospatial analysis.
Design/methodology/approach: The research combines an indicator-based assessment with spatial accessibility analysis. Five original indicators were proposed: Inter-city Connectivity Ratio (ICR), Daily Service Frequency (DSF), Transport Capacity Potential (TCP), Number of Lines per 1,000 Inhabitants (IL), and Bus Stop Density (BSD). Data were obtained from Statistics Poland (GUS), the Metropolitan Transport Authority (ZTM) and GIS-based mapping of stops and 500 m/1 km buffers using QGIS. Thresholds for interpreting the indicators were derived from literature, European metropolitan benchmarks, and international accessibility guidelines.
Findings: The study shows that all analysed cities achieve high levels of inter-city connectivity and service frequency, meeting smart mobility objectives. However, significant micro-scale accessibility gaps are revealed when analysing walking distances at 500 m, particularly in peripheral, low-density residential areas. While average values of BSD and other indicators suggest good accessibility, GIS analysis highlights the need for targeted, local interventions (e.g., new stops or route adjustments) to ensure inclusive mobility. The methodology provides a replicable framework for other metropolitan areas.
Originality/value: This paper contributes to the literature by integrating quantitative efficiency metrics with spatial GIS analysis in the context of smart city mobility. It provides actionable insights for policymakers and transport authorities on aligning public transport services with sustainable urban development goals. The framework and findings can inform planning strategies aimed at improving equity, accessibility, and integration of public transport in metropolitan regions.
Keywords: Public transport efficiency; Smart city; Spatial accessibility; Metropolitan mobility; GIS; Urban transport planning.
Category of the paper: Research paper.

1. Introduction

Urban mobility has become a central pillar of contemporary debates on sustainable urban development and smart city implementation (Rey-Moreno et al., 2023). In the 21st century, cities face unprecedented challenges related to rapid urbanisation, climate change, and increasing socioeconomic inequalities. These dynamics compel urban planners and policymakers to seek innovative and integrative approaches that ensure accessibility, environmental sustainability, economic efficiency, and social inclusiveness (Shao, Min, 2025). Among the various urban systems, public transport stands out as a key enabler of smart city functions (Polis Network, 2016). Efficient, accessible, and integrated public transport systems not only facilitate daily mobility but also support environmental goals, enhance urban cohesion, and improve the overall quality of life (Brzeziński, 2024).

The concept of the smart city encompasses the use of digital technologies and data-driven decision-making to optimise urban infrastructure and services (Chadalawada, 2022). In the realm of transport, smart city frameworks promote solutions such as integrated ticketing, real-time passenger information, intelligent traffic management, and multimodal transport hubs (Darsena et al., 2020; Elassy et al., 2024; Puzio et al., 2025). However, beyond technological innovation, the foundation of any effective transport system lies in its operational efficiency and user-oriented planning (Cazuza de Sousa Junior et al., 2023). Optimization of public transport is therefore not only a matter of digitalization but also of network design, service reliability, and alignment with user expectations (Ejdys, 2014).

Measuring and analysing the effectiveness of public transport becomes essential for any city aspiring to align itself with the smart city paradigm (Mohammadi et al., 2022). Transport efficiency indicators provide valuable tools for understanding the functioning and performance of public transit systems (Transportation Research Board, 2021; Henning, 2011). Indicators such as inter-city connectivity, bus frequency, vehicle availability, stop density, and lines per capita provide quantifiable insights into the quality, reach, and reliability of transportation networks (Chowdhury et al., 2014; Lee, 2025). These measures enable city authorities to assess whether current systems meet mobility demands, highlight areas for improvement, and support evidence-based policymaking. They also facilitate international benchmarking and comparability, as promoted by frameworks such as the OECD/ITF Sustainable Urban Mobility Indicators (2020).

At the same time, comprehensive evaluation requires recognizing both direct and indirect impacts of public transport. Litman (2021) emphasizes that efficiency assessments must consider benefits such as reduced congestion, lower emissions, improved accessibility for non-drivers, and enhanced public health through active mobility. This perspective complements technical indicators by embedding them in a wider framework of sustainability and equity. Similarly, the HiTrans best practice guidelines argue that network quality must be assessed in

terms of competitiveness with private cars, especially in medium-sized European cities where dispersed settlement structures limit transport efficiency (Nielsen et al., 2005).

The Upper Silesian-Zagłębie Metropolis (Górnośląsko-Zagłębiowska Metropolia, GZM) presents a particularly relevant case for exploring these dynamics. As a metropolitan area comprising 41 municipalities, including major cities such as Katowice, Gliwice, Zabrze, Bytom, and Ruda Śląska, GZM constitutes a polycentric urban structure with complex transportation needs. The population density, historical development patterns, and administrative fragmentation have resulted in a diverse and sometimes fragmented transport infrastructure. The establishment of a centralised Metropolitan Transport Authority (ZTM) has been a significant step toward greater integration and coordination of public transport in the region. Nevertheless, disparities in service levels, infrastructure investment, and intercity connectivity remain evident.

This paper focuses on evaluating public transport efficiency in four selected cities within the GZM: Zabrze, Gliwice, Bytom, and Ruda Śląska. These cities were chosen due to their demographic and spatial differences, as well as their strategic location within the metropolis. Each of these cities contributes differently to the regional transport network, with varying levels of service provision and infrastructural development. By applying a set of transport efficiency indicators to these cities, this study aims to identify strengths and weaknesses in their public transport systems and assess their alignment with smart city objectives.

The study employs data from the Central Statistical Office (GUS), the Metropolitan Transport Authority (ZTM), and spatial analysis conducted in QGIS. Five original indicators were proposed: Inter-city Connectivity Ratio (ICR), Daily Course Frequency (DCF), Transport Capacity Potential (TCP), Number of Lines per 1,000 Inhabitants (IL), and Bus Stop Density Indicator (BSD). These indicators not only reflect the operational characteristics of the transport system but also provide a foundation for strategic planning and monitoring.

The originality of this research lies in the combined use of these novel efficiency indicators with spatial accessibility analysis based on GIS. While previous studies have typically focused either on operational performance or on accessibility outcomes in isolation, this paper integrates both perspectives within a single methodological framework. This multidimensional approach provides a new lens for evaluating urban transport systems in medium-sized European metropolitan regions and generates insights that are directly applicable to smart city and sustainable mobility policies.

Furthermore, this research highlights the importance of spatial accessibility, particularly the availability of public transport stops within walking distance of residential areas. Using geospatial tools, the study maps public transport coverage in terms of 500-meter and 1-kilometer buffers around transit stops. This analysis reveals how equitably services are distributed and identifies potential accessibility gaps that may hinder mobility for certain population groups.

In sum, the overarching objective of this article is to demonstrate how efficiency indicators can be effectively applied to assess public transport in a smart city context. By integrating operational, spatial, and social dimensions, the research contributes to the discourse on sustainable mobility and provides practical insights for policymakers in the GZM and beyond.

2. Methods

The methodological framework adopted in this study was designed to enable a comprehensive and multidimensional evaluation of the efficiency of public transport systems as a component of smart city development. The applied approach combines indicator-based assessment with spatial analysis supported by Geographic Information Systems (GIS). This dual perspective allows for both quantitative measurement of transport performance and qualitative evaluation of accessibility patterns.

2.1. Research Design and Data Sources

The research is grounded in secondary data collected from official statistical repositories and administrative bodies responsible for public transport management. In particular, data were obtained from the Local Data Bank of Statistics Poland (GUS) and the Metropolitan Transport Authority (ZTM) of the Upper Silesian-Zagłębie Metropolis. Supplementary information on the spatial distribution of stops was collected and processed using the QGIS software, which enabled integration of transport infrastructure with the spatial structure of the analysed cities.

The methodological design was structured around two complementary components: (1) construction of efficiency indicators and (2) assessment of the spatial coverage of urban areas by public transport stops.

2.2. Efficiency Indicators

To assess the operational and structural dimensions of public transport, five key efficiency indicators were proposed and calculated:

1) **Inter-city Connectivity Ratio (ICR)**

$$ICR = \frac{Number\ of\ lines\ serving\ more\ than\ one\ city}{Total\ number\ of\ urban\ lines} \times 100\%$$

What it measures: the proportion of transport lines that connect more than one city within the metropolis. It reflects how strongly the city's transport network is embedded in the wider metropolitan system rather than being limited to local, intra-urban connections.

Why it matters: high inter-city connectivity reduces fragmentation, improves access to regional labour and education markets, and supports smart city development through integrated mobility.

Interpretation:

- < 20% → weak inter-city integration, risk of isolation (This level of integration indicates that the vast majority of lines are located within municipal boundaries. Therefore, intercity travel relies primarily on private cars).
- 20-40% → partial integration but not sufficient for regional cohesion (Moderate integration reflects partial interconnection, yet still insufficient for a metropolitan area).
- 40% → strong integration, enabling functional metropolitan mobility (High integration denotes that a substantial proportion of transport lines serve inter-city connections).

2) Daily Service Frequency (DSF)

$$DSF = \frac{Daily\ number\ of\ line\ departures}{Number\ of\ urban\ lines}$$

What it measures: the average number of trips operated per line during one day. It indicates how often vehicles arrive at stops, directly affecting passenger waiting time and perceived service quality.

Why it matters: frequency is one of the most critical factors for public transport attractiveness compared to private cars. High frequency reduces waiting time and increases reliability, both of which are central to smart mobility.

Interpretation:

- < 15 trips/line/day → low frequency, users perceive service as unreliable.
- 15-30 → moderate attractiveness but may not compete with cars.
- 30 → high-quality service, supporting sustainable modal shift.

3) Transport Capacity Potential (TCP)

$$TCP = \frac{Total\ daily\ number\ of\ departures}{Population} \times 1000$$

What it measures: the number of daily trips in relation to population size (per 1000 inhabitants). It shows whether the transport supply is adequate to meet the mobility needs of residents.

Why it matters: this indicator links transport capacity with demand (population). It allows to identify undersupply (risk of exclusion) or oversupply (inefficient resource allocation). For smart cities, balancing capacity and demand is key to sustainability.

Interpretation:

- < 5 trips/1000 residents → severe undersupply, risk of transport exclusion.
- 5-15 → acceptable but insufficient to trigger behavioural change.
- 15 → good availability, encouraging public transport use.

4) **Number of Lines per 1000 Inhabitants (IL)**

$$LI = \frac{Number\ of\ bus\ and\ tram\ lines}{Population} \times 1000$$

What it measures: the density of the transport offer in demographic terms, i.e., how many lines are available for every 1000 inhabitants.

Why it matters: it indicates whether residents have multiple route options. A higher value reflects network flexibility, giving users alternatives and reducing overcrowding. In smart city mobility, network diversification is crucial for inclusiveness.

Interpretation:

- < 0.1 → poor coverage, limited choices for passengers.
- 0.1–0.3 → moderate accessibility, adequate for medium-density cities.
- 0.3 → high accessibility, multiple routes support resilient mobility.

5) **Bus Stop Density Indicator (BSD)**

$$BSD = \frac{Total\ number\ of\ bus\ stops\ in\ the\ city}{Area\ of\ the\ city\ (in\ km^2)}$$

What it measures: The indicator reflects the spatial accessibility of public transport by quantifying the density of bus stops per square kilometer. It indicates how evenly the network is distributed across the urban area and how far residents must typically walk to reach the nearest stop.

Why it matters: High density of bus stops ensures short walking distances and equitable access to public transport, especially important in smart city strategies for elderly, disabled, or mobility-impaired users. Conversely, low density may lead to transport exclusion in peripheral or low-density neighbourhoods.

Interpretation:

- < 1 bus stop/km² → poor coverage, long walking distances.
- 1-3 bus stops/km² → moderate coverage, adequate in medium-density cities.
- 3 bus stops/km² → high accessibility, typical of well-developed metropolitan systems.

The Bus Stop Density (BSD) indicator is calculated as the number of public transport stops located within the boundaries of the analysed area divided by the area's surface in square kilometres. To determine its value, it is therefore necessary to accurately count the number of stop points within the studied city or district and precisely determine the area's size. Stop location data can be obtained from official sources (e.g., the Metropolitan Transport Authority) or from databases such as OpenStreetMap using the QuickOSM plugin in QGIS. After loading the stop layer, the dataset can be manually updated to reflect the most current state of the transport infrastructure. The calculation can be supported by GIS tools. For example, in QGIS, the "Count Points in Polygon" algorithm can be applied to automatically count the number of stops within a defined area (e.g., city or district boundaries).

To further evaluate accessibility, buffers with a radius of 500 m and 1000 m can be generated around each stop, as illustrated in Figure 1.



Figure 1. 1 km buffer around the bus stop.

Source: prepared using QGIS.

Analysing the overlap of these buffers with the built-up areas makes it possible to identify zones that meet the statutory recommendations on maximum walking distances to public transport stops included in the Polish housing special act (500 m in cities with more than 100,000 residents, 1000 m in smaller towns). This approach allows not only the calculation of the BSD value but also a spatial diagnosis of areas with potentially limited access to public transport.

The interpretation of the efficiency indicators developed in this study required the adoption of threshold values distinguishing low, moderate, and high performance. Since there are no universally established benchmarks for such indicators, the thresholds were determined through:

- comparative reasoning with European metropolitan areas noted for high transport performance and integration, e.g., Vienna (European Economic and Social Committee, 2004), Copenhagen (OECD, 2009). Ruhr region and Randstad (Centre for Cities, 2016);
- literature evidence highlighting functional requirements of metropolitan public transport (Vuchic, 2005; Priemus and Zonneveld, 2003);
- planning standards and guidelines from international bodies (OECD/ITF, 2020; UITP, 2018) emphasizing accessibility and frequency.

There are no universally established threshold values for the Inter-city Connectivity Ratio (ICR), which measures the share of inter-municipal transit lines. Functional urban area frameworks emphasise the importance of inter-municipal commuting (European Economic and Social Committee, 2004; OECD, 2009), and comparative studies of highly integrated

metropolitan regions, such as the Randstad and Rhine-Ruhr, confirm that extensive inter-city connections are a key component of successful metropolitan transport systems (Centre for Cities, 2016). While studies underline the need for integrated networks (Vuchic, 2005; Priemus, Zonneveld, 2003), they do not propose numeric benchmarks. In this study, ICR values below 20% are interpreted as indicating weak system integration, values between 20 % and 40 % as moderate integration, and those above 40% as strong. The upper threshold reflects empirical modal-split patterns in Vienna, where approximately 39% of trips are undertaken by public transport, which is indicative of a highly integrated system (European Commission (DG MOVE), 2025; European Commission, 2020).

Another critical measure is the Daily Service Frequency (DSF), since service frequency is a key determinant of user satisfaction and modal shift (Vuchic, 2005). Urban planning and accessibility guidelines suggest that a minimum of 2-4 departures per hour, corresponding to roughly 15-30 trips per line per day, is required for an attractive public transport offer (OECD/ITF, 2020). Consequently, fewer than 15 trips per line per day are considered insufficient, 15-30 denote a moderate level of service, and more than 30 indicate a high-quality offer. UITP (2018) also stresses that frequent and reliable service is fundamental to inclusive and accessible mobility systems.

Similarly, there are no formal benchmarks for the Transport Capacity Potential (TCP) expressed as the number of trips per 1000 inhabitants per day. Sustainable transport planning highlights the need to match capacity with demand (Litman, 2021; OECD/ITF, 2020). Against this backdrop, values below 5 trips per 1000 residents indicate undersupply, values between 5 and 15 are interpreted as intermediate, while those above 15 represent adequate supply. These thresholds align with conditions observed in well-integrated metropolitan regions such as the Ruhr area or the Randstad, where public transport serves a substantial share of commuting flows (Centre for Cities, 2016; OECD, 2009).

The Number of Lines per 1000 Inhabitants (IL) also lacks internationally standardised values. Comparative analyses of metropolitan areas demonstrate that higher line densities correlate with greater public transport use (European Commission, 2020). Therefore, values below 0.1 lines per 1000 inhabitants are considered a poor offer, 0.1-0.3 indicate a moderate level, and values above 0.3 are indicative of a good supply.

Finally, the Bus Stop Density Indicator (BSD) should be assessed in relation to accessibility norms. Urban accessibility guidelines recommend walking distances to public transport stops not exceeding 500-1000 metres, which in dense urban areas corresponds to approximately 1-3 stops per km² (European Commission (DG MOVE), 2025; OECD/ITF, 2020; Federal Transit Administration, 2015). Consequently, less than 1 stop per km² denotes poor spatial accessibility, 1-3 stops per km² is considered satisfactory, while more than 3 stops per km² is regarded as very good. This interpretation is consistent with accessibility research and UITP's inclusive mobility guidelines (UITP, 2018).

These thresholds are functional benchmarks informed by literature, planning standards, and regional patterns—not rigid norms. They provide a structured framework for interpreting transport efficiency within smart city contexts and for comparison across cities.

3. Results

The analysis of metropolitan public transport efficiency for Zabrze, Gliwice, Bytom and Ruda Śląska was carried out using a set of indicators assessing inter-city connectivity, service frequency, transport capacity, network density and spatial accessibility.

The ICR values indicate a strong level of inter-municipal connectivity in most of the analysed cities. Bytom achieved the highest share of inter-city lines at 83% (Fig. 2), followed by Ruda Śląska (82%) (Fig.3) and Zabrze (79%) (Fig. 4). Gliwice recorded a lower value of 63% (Fig. 5), which, while below the others, still falls within the high integration category. According to the adopted interpretation thresholds, values above 40% are classified as strong integration, enabling cohesive regional travel and supporting smart city development objectives. From this perspective, all four cities demonstrate high inter-city integration, confirming the importance of a dense, cross-boundary network in metropolitan areas.

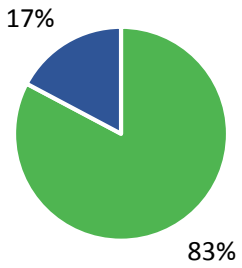


Figure 2. Chart of the percentage of connections with other cities (ICR) for the city of Bytom (green - lines operating in more than one city, blue - lines operating in one city).

Source: own study.

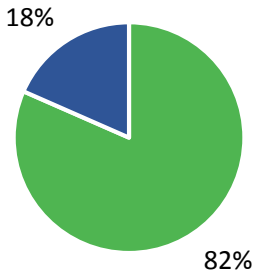


Figure 3. Chart of the percentage of connections with other cities (ICR) for the city of Ruda Śląska (green - lines operating in more than one city, blue - lines operating in one city) .

Source: own study.

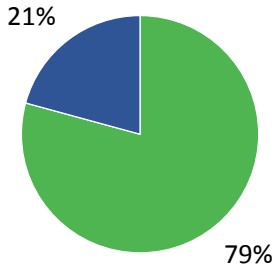


Figure 4. Chart of the percentage of connections with other cities (ICR) for the city of Zabrze (green - lines operating in more than one city, blue - lines operating in one city).

Source: own study.

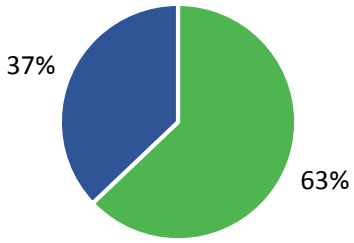


Figure 5. Chart of the percentage of connections with other cities (ICR) for the city of Bytom (green - lines operating in more than one city, blue - lines operating in one city).

Source: own study.

The DSF analysis highlights that service frequency plays a decisive role in transport attractiveness. According to Fig. 6, all analysed cities significantly exceed the high-quality threshold of 30 trips per line per day. Bytom achieves the highest daily service frequency at around 53.7 trips per line, followed by Ruda Śląska (50.3), Gliwice (46.6) and Zabrze (44.4). These results show that all four cities fall into the high-quality group (>30), which helps people choose public transport instead of cars and makes it a real alternative to driving. The results confirm that residents in all analysed cities have access to frequent and reliable services, a key factor for smart and sustainable mobility.

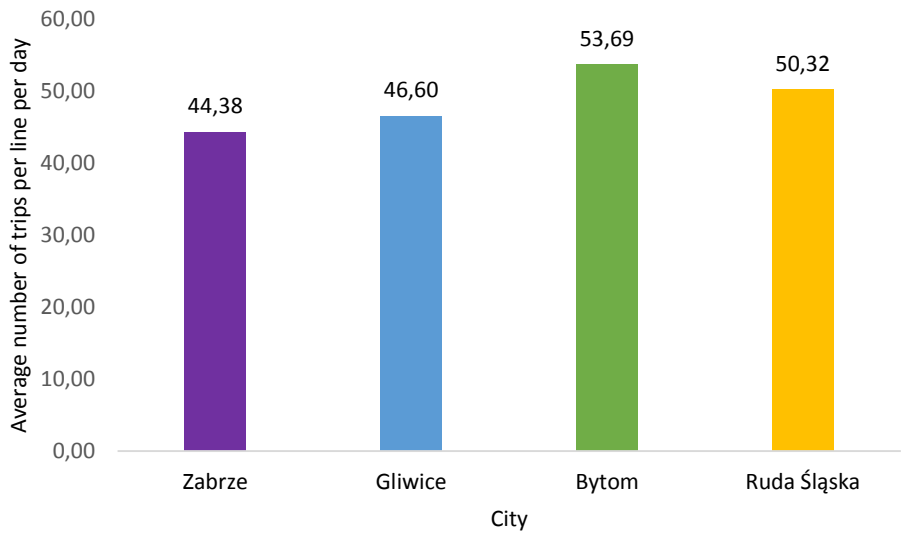


Figure 6. The Daily Service Frequency (DSF).

Source: own study.

The Transport Capacity Potential (TCP) indicator (Fig. 7), measuring the total number of daily trips per 1000 residents, further highlights differences in service provision.

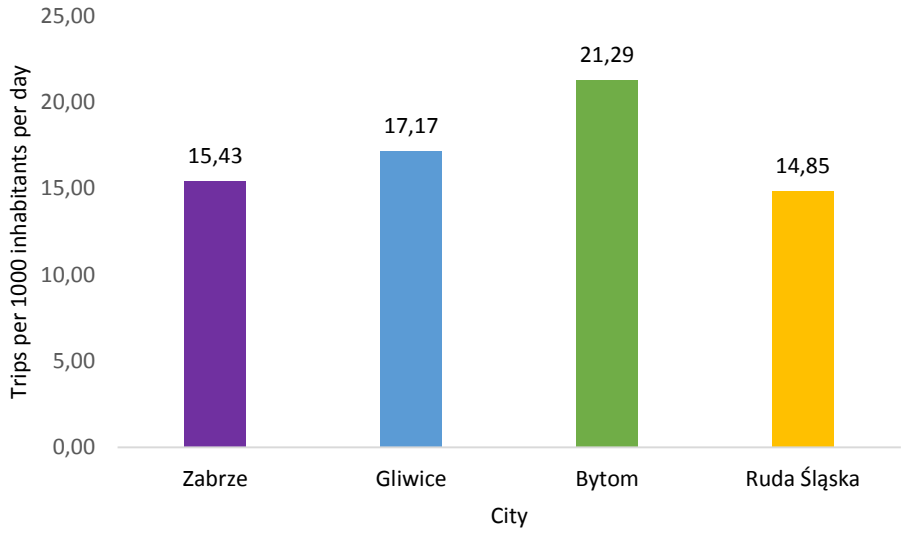


Figure 7. The Transport Capacity Potential (TPC).

Source: own study.

Bytom records the highest value with 21.29 trips/1,000 inhabitants, followed by Gliwice (17.17), Zabrze (15.43) and Ruda Śląska (14.85). According to the adopted interpretation, <5 trips/1000 residents/day indicates a severe undersupply and a risk of transport exclusion, 5-15 represents an acceptable but insufficient level to trigger behavioural change, while values above 15 denote good availability that encourages public transport use. Bytom clearly exceeds this threshold, confirming its well-developed service provision, while Gliwice and Zabrze also fall within the good availability category. Ruda Śląska, with a value just below 15, remains slightly behind and may require targeted improvements to strengthen accessibility. The Number

of Lines per 1000 Inhabitants (IL) reflects the density of the transport offer in demographic terms — how many bus and tram lines are available for every 1000 residents. This indicator matters because a higher value provides passengers with multiple route options, increases network flexibility, and reduces the risk of overcrowding. It is also crucial for inclusiveness in smart city mobility, because a varied network gives all users fair access. In the analysed cities, IL ranges from 0.30 in Ruda Śląska to 0.40 in Bytom (Fig. 8).

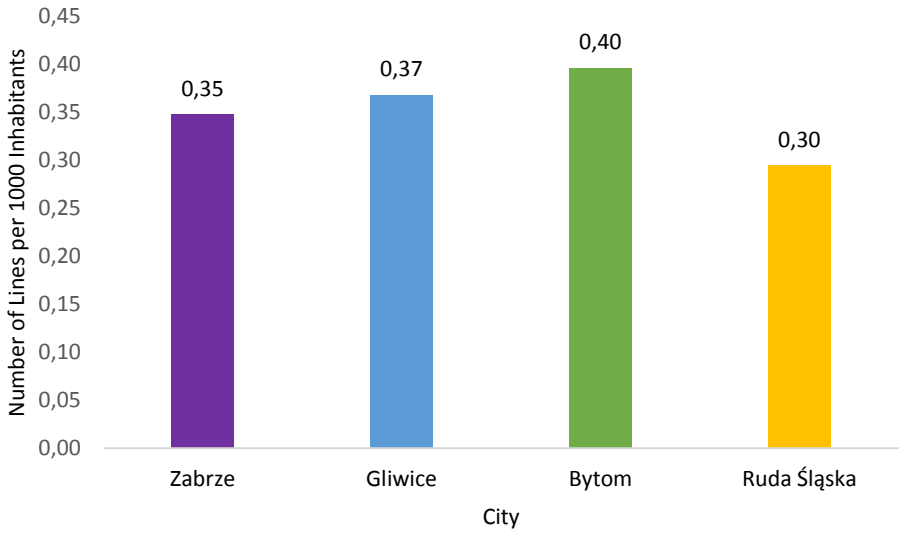


Figure 8. The Number of Lines per 1000 Inhabitants (IL).

Source: own study.

According to the adopted interpretation thresholds, <0.1 indicates poor coverage and limited choices for passengers, 0.1-0.3 denotes moderate accessibility adequate for medium-density cities, while >0.3 reflects high accessibility, where multiple routes support resilient and inclusive urban mobility. Thus, Bytom and Gliwice, both above 0.35, provide high accessibility; Zabrze also falls within this high category, while Ruda Śląska, at 0.30, remains at the upper end of moderate accessibility.

The last indicator analysed is the bus stop density index (BSD), which reflects the spatial accessibility of public transport, measured by the number of stops per square kilometer. As shown in Figure 9, Zabrze has the highest BSD at 4.69 stops/km², followed by Bytom (4.3 stops/km²), Ruda Śląska (3.67 stops/km²) and Gliwice (3.14 stops/km²). According to the adopted interpretation (<1 stop/km² – poor coverage; 1-3 stops/km² – moderate; >3 stops/km² – high accessibility), all analysed cities exceed the 3 stops/km² threshold, confirming a high level of accessibility typical of well-developed metropolitan systems. This density ensures short walking distances and equitable access, which is particularly important in smart city strategies targeting the elderly and mobility-impaired users.

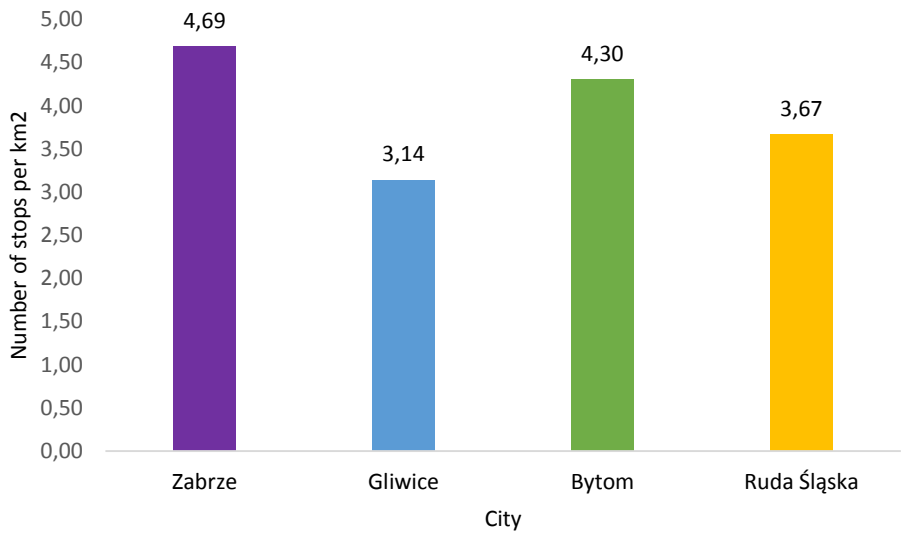


Figure 9. The Bus Stop Density (BDS).

Source: own study.

A detailed GIS analysis of the spatial coverage provides further insights into the distribution of stops and accessibility gaps. Figures 10-13 illustrate the location of stops and the 1 km buffers in Zabrze, Gliwice, Bytom and Ruda Śląska. At this buffer level, nearly all built-up areas are covered, demonstrating that the majority of residents can reach a stop within a 10-15 minute walk. The highest spatial coverage is observed in Zabrze and Bytom, where even peripheral districts are within the 1 km service area. The maps were prepared in QGIS using spatial data from OpenStreetMap, which ensured both accuracy and comparability of the analysis across cities. The integration of OSM data allowed for the identification of peripheral gaps that are not always visible in official statistics, highlighting the added value of open-source geoinformation. This methodological approach offers a clear and reproducible way of assessing public transport accessibility, which can also be applied to other cities and metropolitan areas.

As shown in Figure 9, Zabrze records the highest bus stop density among the four analysed cities. This finding is also reflected in the 1 km buffer analysis presented in Figure 10, which demonstrates that more than 80% of built-up residential areas are located within the service area. Only small peripheral fragments remain outside the buffer, confirming the generally high level of accessibility in the city.

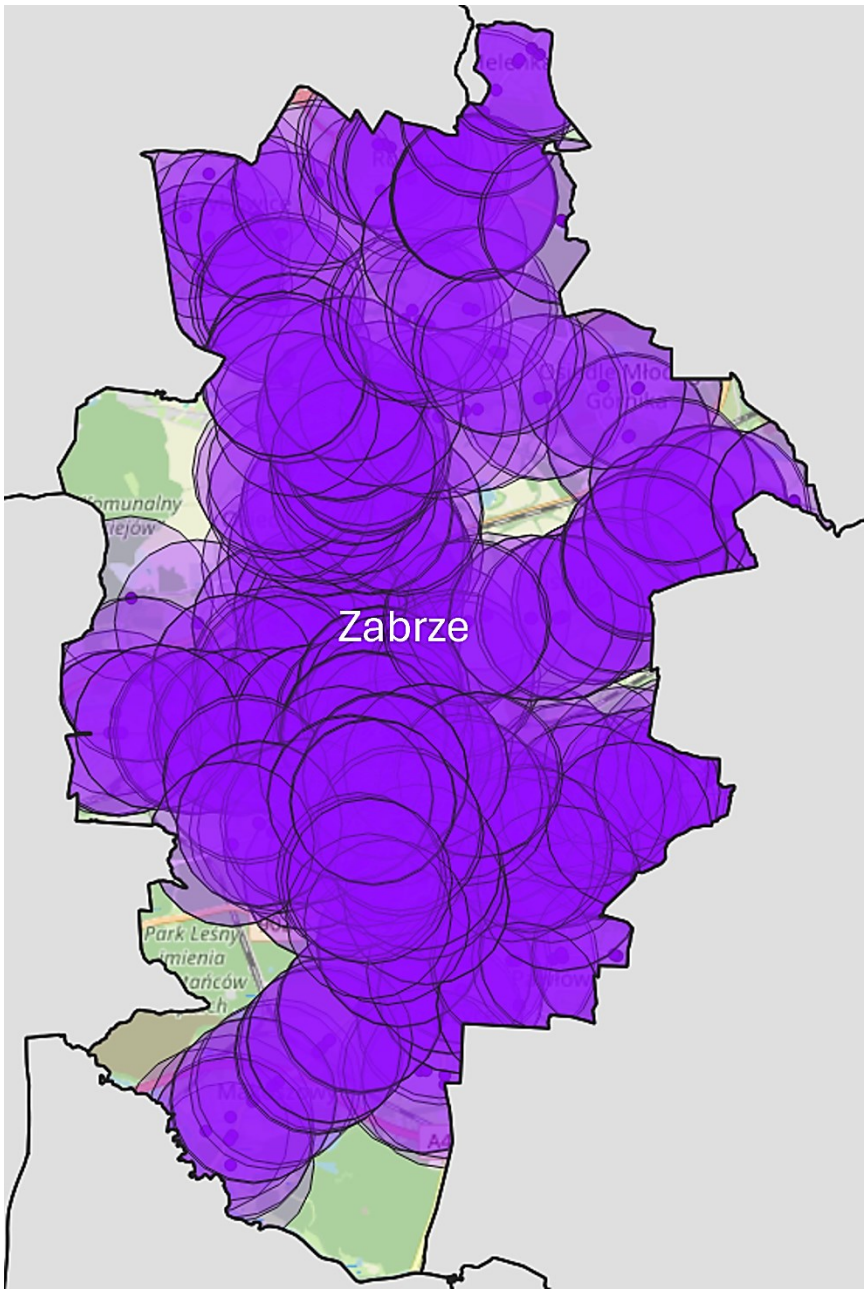


Figure 10. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

As can be seen in Figure 11 for Gliwice, the overall coverage is high, yet some accessibility gaps remain on the periphery. Nearly all central and inner-district built-up areas fall within the 1 km buffer, but small fragments of development are uncovered. These include the northernmost built-up area of Czechowice on the left of the map and a housing estate above the Ostropa district near the Sośnicowice boundary above the A4 corridor. These gaps correspond to zones of dispersed housing, whereas the dense urban core exhibits full coverage, indicating broadly satisfactory accessibility at the 1 km scale.

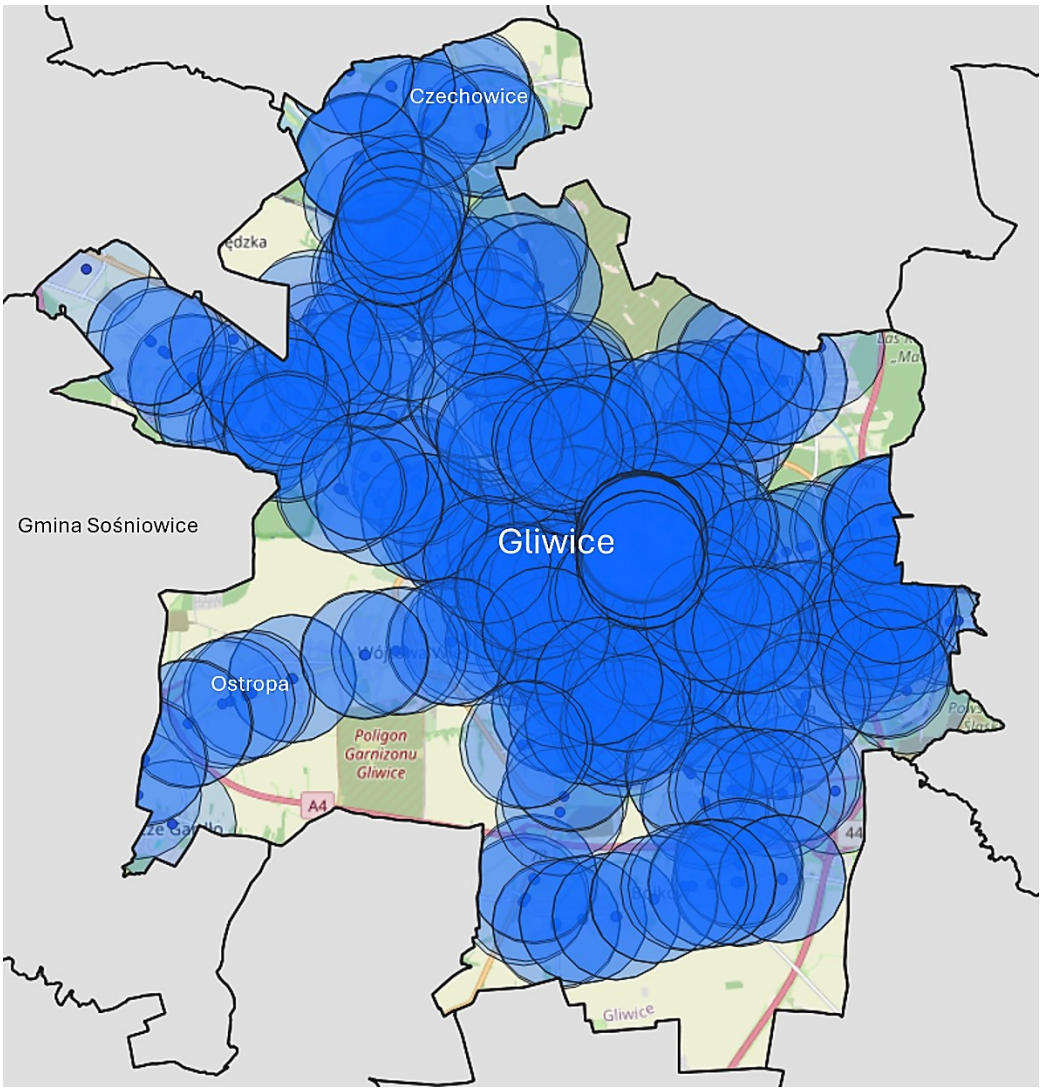


Figure 11. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Gliwice.

Source: own study, prepared using QGIS and OpenStreetMap data.

The map for Bytom in Figure 12 shows that almost all of the city's residential development is located within a 1-kilometer buffer. The very few uncovered fragments are situated on the periphery and are typically industrial or undeveloped areas rather than residential zones. The compact settlement structure of Bytom contributes to its nearly complete service coverage, with excellent accessibility in the city centre and surrounding districts.

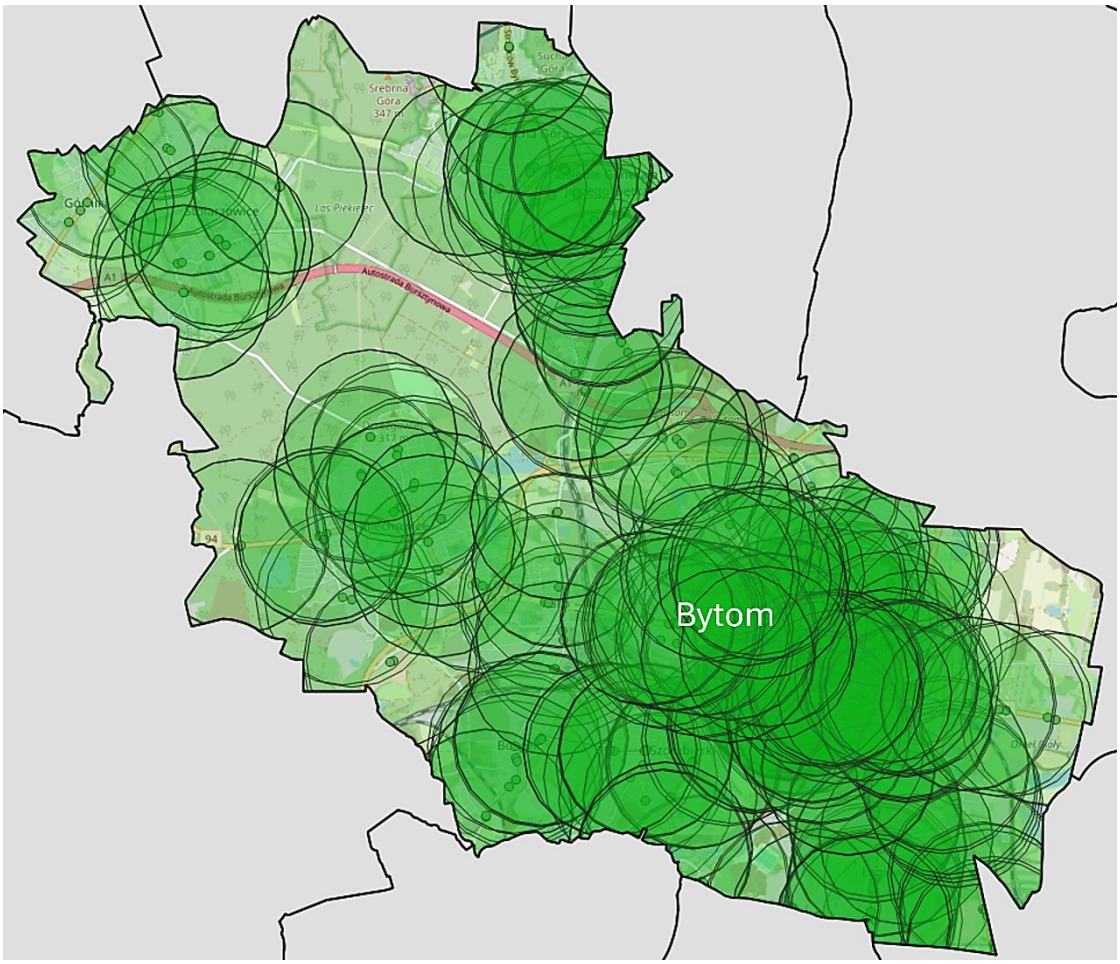


Figure 12. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Bytom.

Source: own study, prepared using QGIS and OpenStreetMap data.

Most Ruda Śląska residents also have convenient access to public transport within a 1 km walk (Figure 13). The central and inner-city districts are fully covered, with only some areas on the southern and western outskirts lying outside the buffer. These gaps correspond to more dispersed or mixed-use development patterns and larger areas of greenery or former industrial land. Nevertheless, the majority of the built-up area maintains good spatial accessibility to stops.

In summary, the 1 km buffer analysis highlights that while all four cities perform well in terms of stop coverage and meet smart mobility objectives, there are localised peripheral gaps in low-density districts. These findings provide a foundation for fine-grained 500 m buffer analyses to target micro-scale improvements.

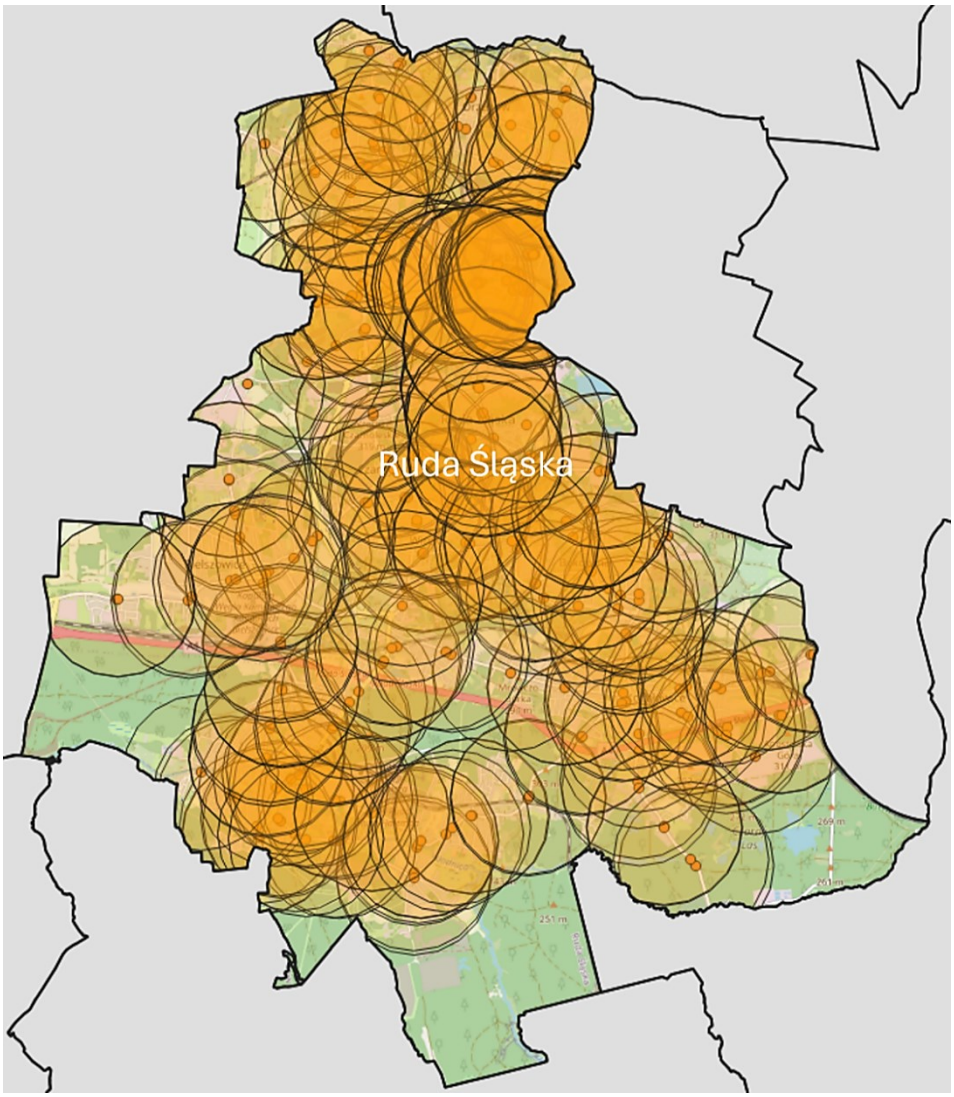


Figure 13. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Ruda Śląska.

Source: own study, prepared using QGIS and OpenStreetMap data.

As shown in Figure 14, in north Zabrze, there is a large light-grey built-up fragment on the left (labelled "1" in the thesis) and several housing/streets (labelled "2") lying beyond 500 m from the nearest stop; on the right side the coverage improves, yet a part of Rokitnica remains outside the buffer (labelled "3"). In south Zabrze (Fig. 15), coverage is generally good, but a built-up section of Maciejów at the top-right edge near the Gliwice border has no stop within 500 m (labelled "4"); other southern areas are acceptably covered.

Taken together, these findings show why BSD >3 stops/km² is a helpful first-order signal (high accessibility), but micro-scale gaps at 500 m matter for everyday usability and equity. For Zabrze this points to targeted, low-cost fixes, e.g., adding or relocating stops in Rokitnica and Maciejów.

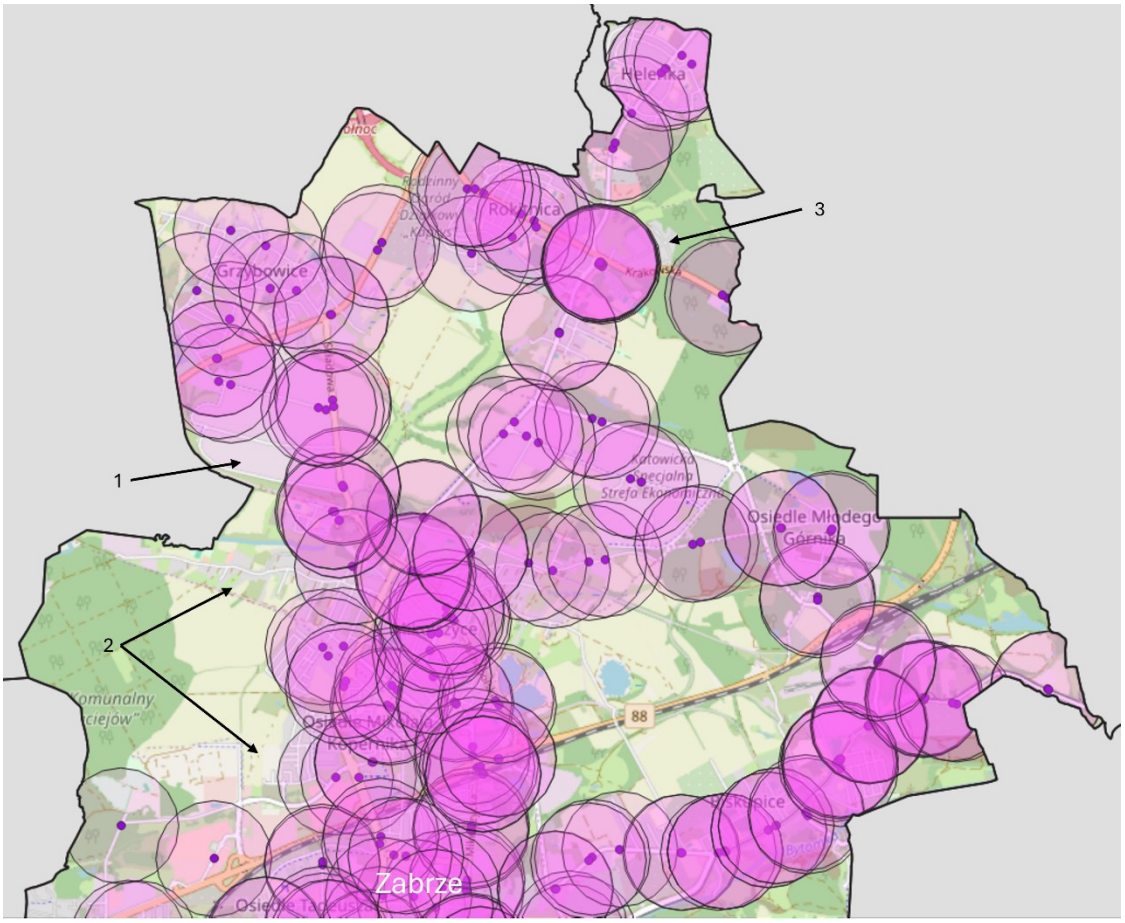


Figure 14. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the northern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

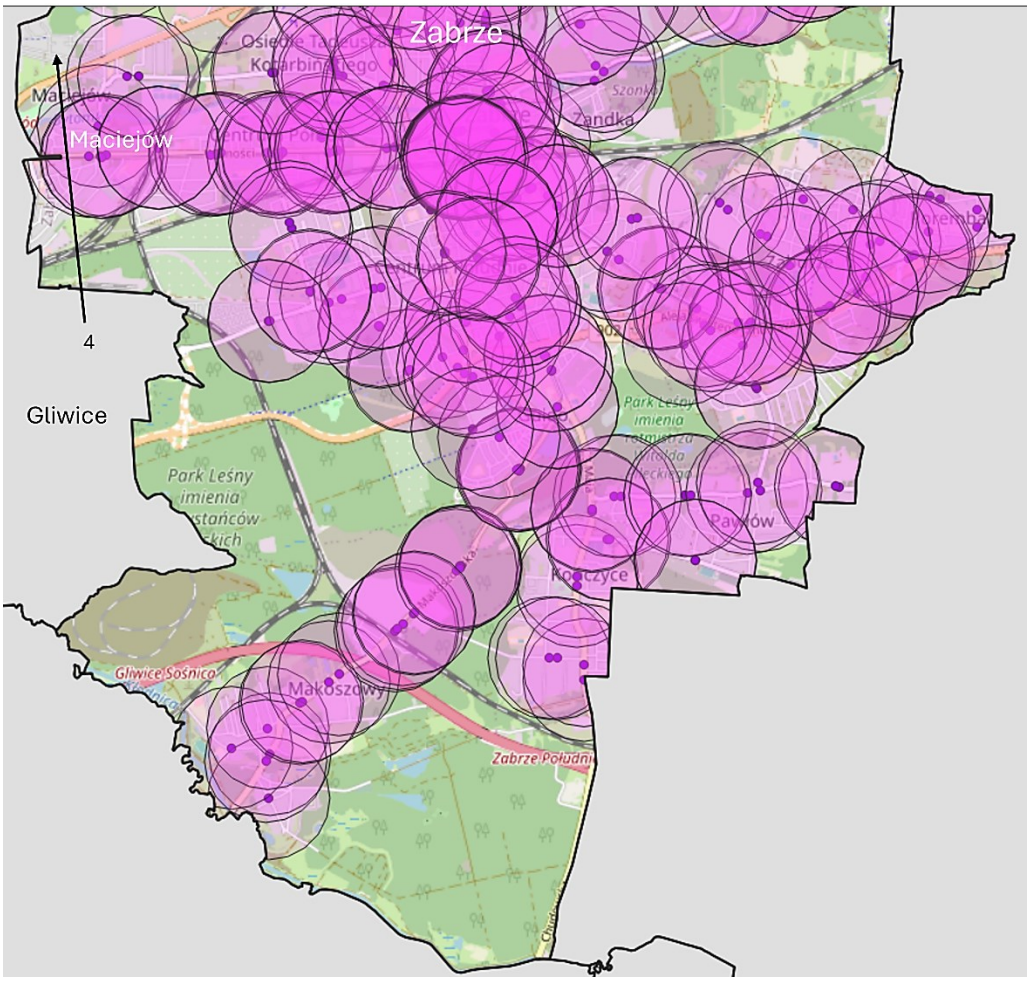


Figure 15. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the southern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

While the citywide BSD in Gliwice exceeds the high-accessibility threshold, a closer look at walking-distance coverage reveals important local differences. At the stricter 500 m walking threshold, north Gliwice (Fig. 16) shows clear coverage gaps: a larger uncovered area in Żerniki, located east of the A1, and additional uncovered built-up fragments in Czechowice (the northernmost part of the city). These are continuous residential patches beyond 500 m from the nearest stop, signalling a need for targeted adjustments.

In south Gliwice (Fig. 17), there are many small gaps between the 500 m buffers, mostly in single-family housing areas where buildings are spread out. Because of this layout, some homes are still over 500 m from a stop, even though there are many stops overall. This shows how the average BSD can hide these small local access problems".

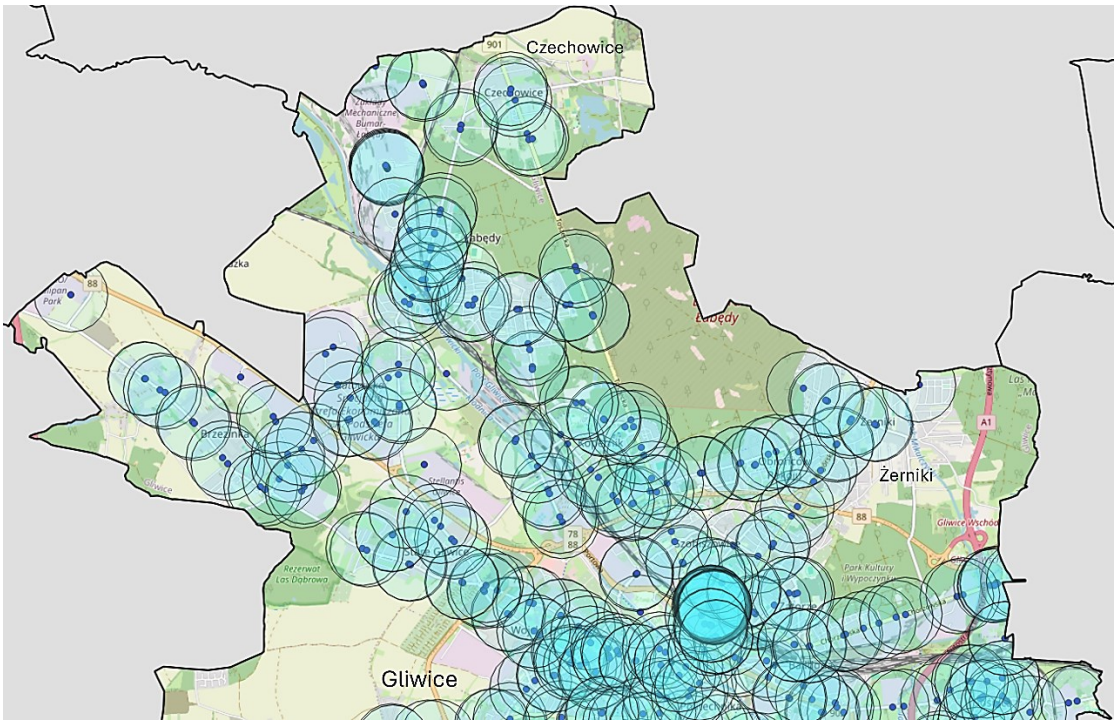


Figure 16. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the northern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

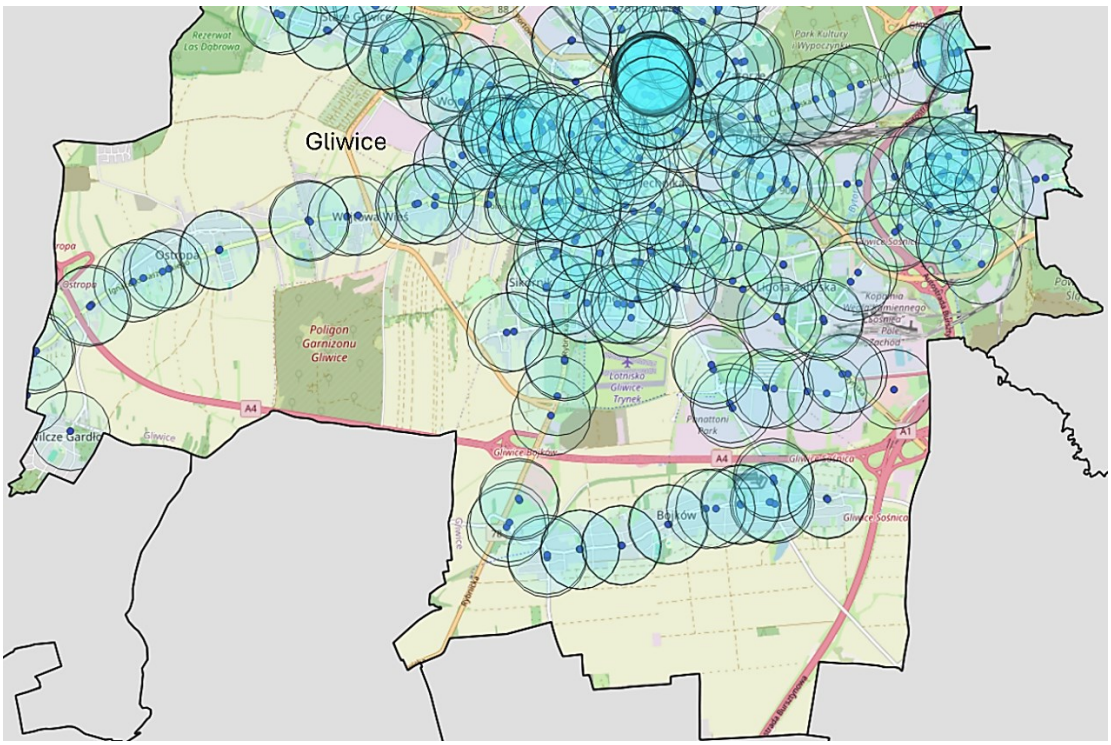


Figure 17. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the southern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

Bytom has one of the highest stop densities among the analysed cities (BSD ≈ 4.3 stops/km²; Fig. 9), which on average terms suggests short walking distances and good overall network coverage. However, as can be seen in Figure 18, at the stricter 500 m buffer, some housing estates and single-family streets appear outside the service area. While central Bytom is well covered, the deficits are mainly located on the city's edges in low-density residential zones. This implies a need for small-scale interventions—such as adding or relocating stops or making short route adjustments—to translate the high citywide BSD into uniform 500 m walking access.

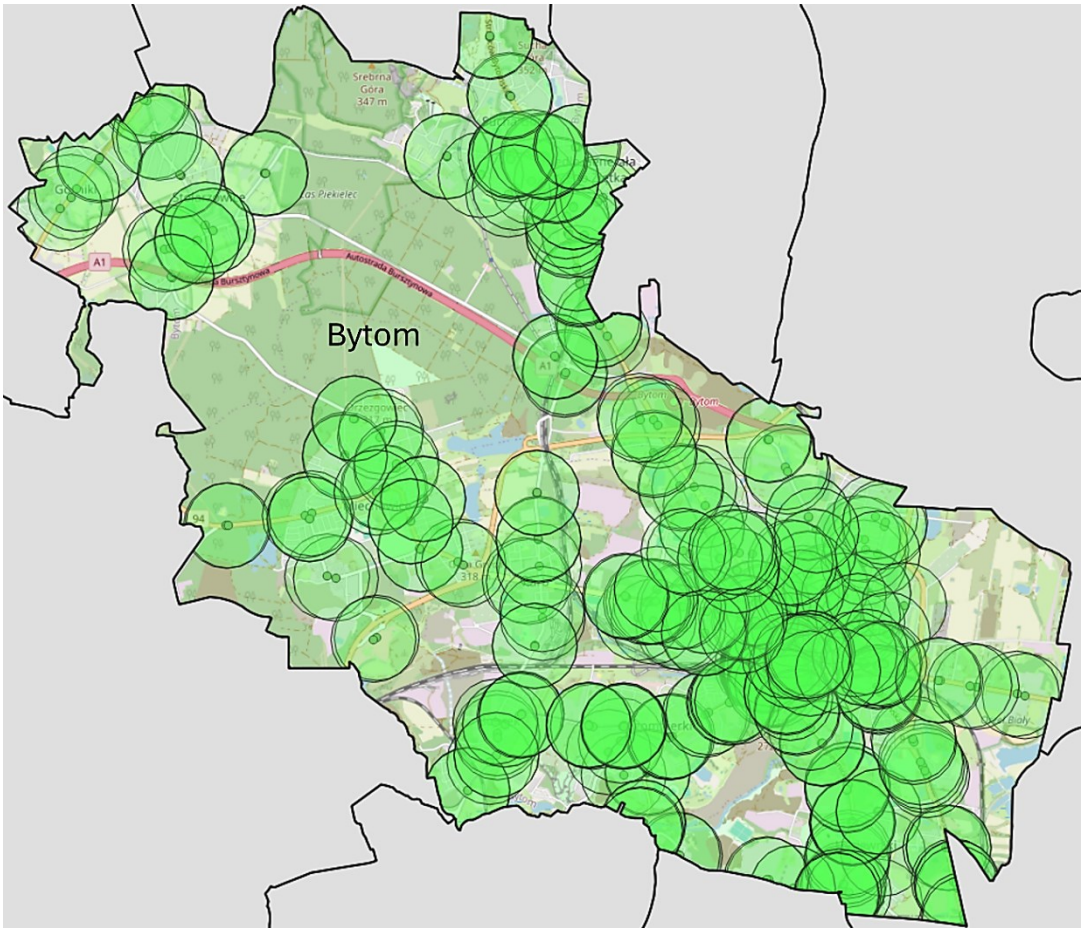


Figure 18. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop in Bytom.

Source: own study, prepared using QGIS and OpenStreetMap data.

Ruda Śląska achieves BSD ≈ 3.7 stops/km² (Fig. 9), also placing it above the high-accessibility threshold in average terms. As shown in Figure 19, at the 500 m buffer, accessibility drops more noticeably in these peripheral low-density areas. Central neighbourhoods maintain good coverage. Addressing these gaps would require denser stop spacing or minor route adjustments in critical residential pockets.

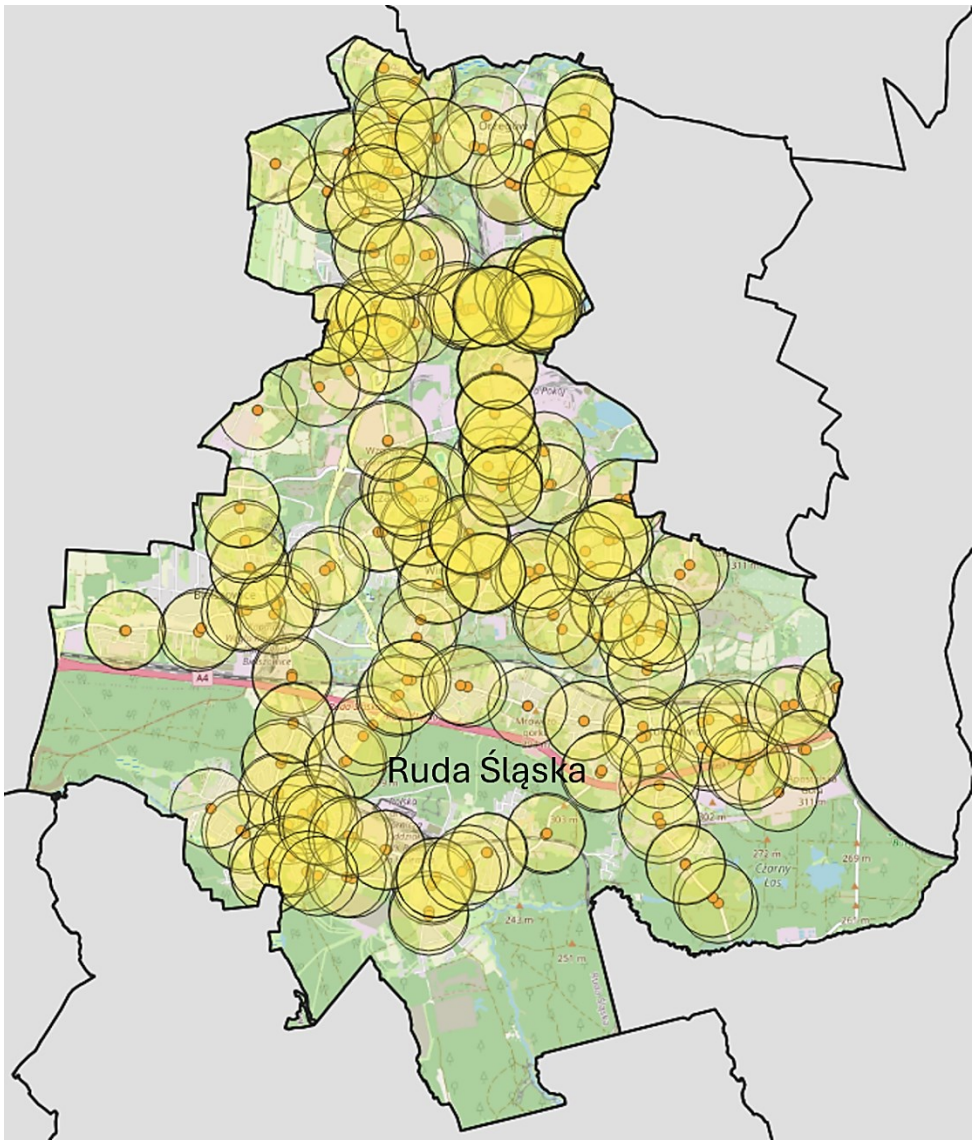


Figure 18. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop in Ruda Śląska.

Source: own study, prepared using QGIS and OpenStreetMap data.

Summarising the analyses of the 500 m buffer in all four cities, it can be seen that despite high accessibility throughout the city, there are local gaps in services in the peripheral districts with low population density. These results suggest that micro-scale planning interventions, such as the addition of stops, minor route adjustments or complementary first/last-mile solutions, could enhance inclusiveness and ensure that even residents on the urban fringe have equitable access to public transport.

4. Discussion

The findings of this study confirm that public transport systems in Zabrze, Gliwice, Bytom and Ruda Śląska exhibit high levels of efficiency when measured through the proposed indicators. Strong inter-city integration (ICR > 60%) and high daily service frequency (DSF > 44) align with international evidence emphasizing the importance of connectivity and frequency for modal shift towards public transport. Vuchic (2005) as well as the Centre for Cities (2016) highlight that dense, cross-boundary networks and frequent services are prerequisites for making public transport competitive with private cars in metropolitan regions. Our results resonate with these conclusions, demonstrating that the analysed GZM cities already meet such benchmarks.

At the same time, the Transport Capacity Potential (TCP) values (14.85-21.29 trips per 1,000 inhabitants) and the Number of Lines per 1000 Inhabitants (IL, 0.30-0.40) indicate that service supply in demographic terms is adequate but heterogeneous. Similar patterns were identified in OECD/ITF (2020) reviews, which stress that cities with strong aggregate capacity may still face localized undersupply, particularly in low-density suburban districts. Our results for Ruda Śląska (TCP below 15) confirm this risk, suggesting that capacity allocation must be fine-tuned to match local demand.

The spatial accessibility analysis using bus stop density (BSD) and GIS-based buffers provides further insights. While all four cities surpass the high-accessibility threshold (>3 stops/km²), the 500 m buffer analysis reveals gaps in peripheral areas. Comparable discrepancies between average indicators and local accessibility outcomes have been documented in Nordic smart city strategies (Müller-Eie, Kosmidis, 2023) and OECD/ITF (2020) guidelines, which warn against relying solely on macro-scale efficiency measures. Our results for districts such as Rokitnica in Zabrze and Żerniki in Gliwice illustrate these challenges, showing how inclusiveness and equity may be compromised despite overall high performance. Based on these insights, it is recommended to implement targeted, low-cost interventions such as:

- adding or relocating stops in underserved areas,
- minor route adjustments,
- first/last-mile solutions (e.g., micro-mobility, demand-responsive transit) (Manning and Babb, 2023; Ferguson and Sanguinetti, 2021).

In doing so, the GZM can strengthen both the efficiency and equity of its public transport system, thereby advancing its smart city objectives.

The originality of this study lies in the integration of quantitative performance indicators with GIS spatial analysis. Previous research often assessed either operational efficiency (Henning, 2011; Chowdhury et al., 2014) or accessibility outcomes (European Commission, 2020) in isolation. By combining both approaches, our study provides a multidimensional

framework that better reflects smart city principles, where efficiency, inclusiveness, and sustainability must be pursued simultaneously (Brzeziński, 2024; Shao, Min, 2025; Tamakloe et al., 2024). This methodological integration fills an existing gap and offers a replicable tool for other metropolitan regions.

Finally, the implications of our findings support international trends such as the "15-minute city" and transit-oriented development (OECD/ITF, 2020). At the same time, international evidence demonstrates that efficiency indicators must be embedded in broader frameworks of sustainability and resilience (Kaiser and Schaffer, 2025). Litman (2021) stresses that evaluation of public transport must account for external benefits such as reduced congestion, environmental gains, and health impacts, while Müller-Eie and Kosmidis (2023) point out that Nordic smart city mobility strategies often fail in addressing equity. Insights from Saudi Arabian cities suggest that smart mobility solutions can significantly enhance operational efficiency when supported by robust infrastructure and effective governance (Alotaibi et al., 2025). Similar conclusions are drawn in reviews of smart public transport systems worldwide (AlFalasi, 2025). Furthermore, energy efficiency considerations (Augustyn, 2025) and sustainability indicators (da Silva Tomadon et al., 2024) provide an additional dimension for strengthening policy decisions.

Building on these insights, future research should aim to operationalise these broader perspectives in the context of the GZM. First, the scope of analysis ought to be extended to all municipalities within the metropolis and compared with other Polish and European regions to capture inter-metropolitan diversity. Incorporating dynamic data sources (real-time GPS, ticketing and mobile phone data) would allow for monitoring temporal variations in efficiency and service quality.

5. Summary

This study set out to evaluate the efficiency of public transport systems in four cities of the Upper Silesian-Zagłębie Metropolis (Zabrze, Gliwice, Bytom, Ruda Śląska) using a combination of five original indicators and GIS-based accessibility analysis. The proposed indicators – Inter-city Connectivity Ratio (ICR), Daily Service Frequency (DSF), Transport Capacity Potential (TCP), Number of Lines per 1,000 Inhabitants (IL), and Bus Stop Density (BSD) – provided a multidimensional framework for assessing operational, demographic, and spatial aspects of public transport performance. By linking these measures to international benchmarks (OECD/ITF, DG MOVE, UITP, SUMI), the study demonstrated both strong regional integration and local weaknesses that may limit inclusiveness.

While many previous works have focused either on operational measures (Henning, 2011; Chowdhury et al., 2014) or accessibility norms (European Commission, 2020; UITP, 2018), this paper combines both approaches. The findings show that high aggregate values of connectivity, frequency, and stop density can mask micro-scale inequalities visible only through fine-grained GIS analysis, a point also emphasised in international studies of metropolitan mobility (OECD/ITF, 2020; Müller-Eie, Kosmidis, 2023).

The results confirm that the four analysed cities meet or exceed many thresholds for high-quality service, aligning with literature that underscores the role of frequency, connectivity, and diversity of routes in fostering modal shift and competitiveness with private cars (Vuchic, 2005; Centre for Cities, 2016). At the same time, spatial gaps at the 500 m scale demonstrate that equity and inclusiveness remain challenges even in generally well-performing systems. This echoes broader critiques in the literature that smart mobility strategies often neglect vulnerable groups and localised accessibility (Litman, 2021; Müller-Eie, Kosmidis, 2023).

By explicitly combining indicator-based efficiency assessment with spatial equity analysis, the study offers a replicable framework for policymakers and practitioners. The approach highlights not only where systems perform strongly but also where targeted, low-cost interventions such as additional stops, minor route adjustments, or first/last-mile solutions can enhance inclusiveness. In doing so, the paper contributes to the international discourse on smart and sustainable mobility by showing how locally adapted measures can be grounded in globally recognised standards.

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ANALYSIS OF SIGNAL ACCURACY FROM TECHNICAL INDICATORS FOR INVESTMENT IN GLOBAL STOCK MARKET INDICES

Diana KRAL-GRABKA[1], Krzysztof PODGÓRSKI[2*]

[1] University of Economics in Katowice; diana.kral-grabka@ue.katowice.pl, ORCID: 0000-0001-5568-6335
[2] University of Economics in Katowice; krzysztof.podgorski@ue.katowice.pl, ORCID: 0000-0002-7549-1997
* Correspondence author

Purpose: The article presents innovative technical analysis indicators, the so-called vanguard indicators, and compares their effectiveness with classic indicators and the "buy and hold" strategy based on the analysis of 63 global stock market indices. The aim of the study was to evaluate the accuracy of signals generated by selected technical analysis indicators in the context of investing in global stock market indices. The research utilized classic signals produced by chosen technical analysis indicators, as well as their opposite signals, referred to later in the article as newly developed "vanguard" indicators. The results of both strategies were then compared to the "buy and hold" strategy, representing a passive investment approach.
Design/methodology/approach: The database used in the study contained historical quotations of 63 global stock market indices from all continents, covering the period from the inception of each index up to December 31, 2023. Quantitative historical data analysis and statistical tests using Excel and the GRETL program were used.
The following classic technical analysis indicators were included in the study: RSI, CCI, W%R, DM, and ST. The study verified the following research hypotheses: H1: The application of an investment strategy utilizing the developed Vanguard Indicators is economically more advantageous than the use of existing Classic Indicators for major global stock market indices, H2: The application of an investment strategy utilizing the developed Vanguard Indicators is economically more advantageous than the use of the "Buy and Hold" Strategy for major global stock market indices, H3: The use of Vanguard Indicators demonstrates the highest accuracy regardless of geographical location.
Findings: The results showed that newly developed vanguard indicators generate statistically higher rates of return, especially outside America, where their effectiveness was comparable to the passive strategy. The study suggests that selecting the most effective indicator from the vanguard group for a given index allows to maximize profits.
Research limitations/implications: A limitation of the conducted research was the number of classic technical analysis indicators included in the study. The indicators were selected based on criteria that allowed for their values to be calculated using Microsoft Excel and an access to high-frequency data. One of the key limitations of the conducted study is also the omission of transaction costs, price slippage, and liquidity constraints, which may significantly affect the actual effectiveness of the analyzed investment strategies.

Practical implications: The research results can be used to shape the investment decisions for investors.
Originality/value: The literature contains a limited number of studies comparing the accuracy of technical analysis indicators across markets from different regions of the world; most research tends to focus on individual continents. Moreover, studies assessing the accuracy of indicators for index-based investments are typically based on short research periods spanning only a few or several years while overlooking many years of index existence, which also represents a research gap worth addressing.
Keywords: technical analysis indicators, global stock market indices, active investing, buy-and-hold strategy.
Category of the paper: research paper, conceptual paper.

1. Introduction

Investors have always sought tools to help them make informed investment decisions. One such tool is technical analysis indicators, which provide easy-to-interpret signals for initiating or terminating transactions. A common issue raised in the literature and observed in investment practice is the accuracy of these signals, as it impacts individual strategies and final investment outcomes. Technical analysis indicators are applicable in various markets. However, with the increasing popularity of ETF funds, it has become easier to invest in stock market indices, eliminating the need to create a composite basket of individual shares. Now, it only requires the purchase of specific participation units that represent the investor's index of interest (Mitrenga, 2013). Analyzing the accuracy of signals generated by technical analysis indicators, using stock market indices as an example, appears to be an essential issue from both investment theory and practice. This issue is rooted in two key economic theories: the theory of efficient markets, which posits that the prices of financial assets reflect all available information (Dobrowolski, 2014), and the theory of technical analysis, which assumes that prices move according to specific patterns known as trends (Paluszak, Wisniewska-Paluszak, 2018).

The article aims to assess the accuracy of signals generated by selected technical analysis indicators when investing in global stock market indices. The study utilizes classic signals generated by selected technical analysis indicators and opposing signals, referred to in the remainder of the article as "avant-garde." The results of both strategies were then compared to those of the buy-and-hold strategy, which represents a passive investment style.

Technical indicators yield variable signal accuracy across global stock market indices (Shynkevich et al., 2017). In the preliminary studies reviewed, Moving Average Convergence Divergence (MACD) appears in four analyses and Relative Strength Index (RSI) in three, while diverse moving averages and other indicators appear in individual reports (Anghel, 2015). Three studies report quantitative accuracy rates: a Random Forest model attained 80% accuracy on NASDAQ, and support vector machine approaches on the S&P 500 reached 75.4% to 82.6%

accuracy (Cervelló-Royo, Guijarro, 2020). Several papers note that optimized or combined indicators outperform standard parameter settings (Fayek et al., 2013). Key findings include:

- Emerging markets (such as indices in China, India, and Hong Kong) show stronger performance of technical analysis methods than some developed markets (Stavytskyi, Taraba, 2020).
- Developed market indices (e.g., the S&P 500 and FTSE) exhibit mixed results, with some studies noting high accuracy and others reporting poorer performance (Shynkevich et al., 2017).
- Short-term forecasts benefit from aligning data window lengths with forecast horizons, while long-term analyses indicate that parameter optimization improves investment return metrics (Shynkevich et al., 2017).

These results indicate that signal accuracy from technical indicators depends on the indicator chosen, the market context, and the analytical methods employed (Shynkevich et al., 2017).

The preliminary analysis of the literature revealed diverse research findings on the accuracy of technical indicators for indices from various geographic locations. The proposed study encompasses as many as 63 global stock market indices over the most extended possible period, from the beginning of each index to December 31, 2023, i.e., the last completed year when the research was initiated. The study was conducted using an MS Excel spreadsheet and the GRETL program, which was employed to perform statistical tests.

The following hypotheses were verified in the study:

- **H1**: An investment strategy employing the developed Avant-Garde Indicators is more economically advantageous than existing Classic Indicators for the leading world stock market indices.
- **H2**: An investment strategy employing the developed Avant-Garde Indicators is more economically advantageous than the Buy-and-Hold Strategy for the leading world stock market indices.
- **H3**: The use of Avant-Garde Indicators demonstrates the highest accuracy regardless of geographic location.

The article consists of seven sections. Section 1 is an introduction to the topic. Section 2 presents the individual technical analysis indicators used in the research, along with the method for interpreting the signals they generate. Section 3 contain sanoverview of previous studies on the accuracy of technical indicators for investments in stock market indices. Section 4 presents the adopted research methodology in detail. Section 5 discusses the research results. Section 6 offers conclusions and a discussion of the result sobtained by Rother researchers. The final section provide sinformation on the sources of financing for the article. The article concludes with a table that presents the exact list of global stock market indices examined.

2. Technical Analysis Indicators as Determinants of Trading Signals

Technical analysis is a method of forecasting the prices of financial instruments. It enables the prediction of future trends based on historical prices and trading volume (Murphy, 1999). Many techniques are employed in technical analysis, one of which is the use of indicators (Pilipchenko et al., 2021). A diverse range of designs characterizes technical analysis indicators. Some are calculated based solely on prices, while others are based on volumes. Due to the lengthy research period and the resulting availability of data, the study employed indicators that do not account for volume in their design. Oscillators often used by investors were employed, i.e., indicators that allow for the identification of oversold and overbought levels (Brown, 1999), such as Relative Strength Index (RSI), Commodity Channel Index (CCI), Williams Percent Range (W%R), DeMarker (DM), and Stochastic Oscillator (ST).

The Relative Strength Index (RSI) is an indicator created by Welles Wilder (1978) that compares the upward and downward movements of closing prices over a given period (see Formula 1).

$$RSI = 100 - \frac{100}{1+RS} \text{where} RS = \left(\frac{a}{b}\right) \quad (1)$$

where:

a – average value of the increase in closing prices in the analyzed period,

b – average value of the closing price decline for the analyzed period.

The indicator takes values from 0 to 100. Values above 70 (and, in the conservative variant, above 80) indicate that the market is overbought, signaling the opening of a short position or the closing of a long one. In turn, values below 30 (in the conservative variant below 20) indicate that the market is oversold, signaling the opening of a long position or the closing of a short one (Panigrahi et al., 2021).

The Commodity Channel Index, developed by Donald Lambert (1983), measures the difference between the current price and the average price for a given period (see Formula 2).

$$CCI = \frac{1}{0{,}015} * \frac{CT - SMA(CT)}{\sigma(CT)} \text{ where } CT = \frac{C_{max} + C_{min} + C_z}{3} \quad (2)$$

where:

CT – typical rate,

C_{max} – maximum rate,

C_{min} – minimum rate,

C_z – closing rate,

SMA – simple moving average,

σ– averages standard deviation.

The CCI does not have a strict range. Values below -100 indicate oversold conditions, signaling the opening of a long position or the closing of a short one. In contrast, values above 100 suggest overbought conditions, which signal taking a short position or closing a long one (Carroll, Fusilier, 1997).

Williams Percent Range (W%R) is an indicator by Larry Williams (1979). The indicator's value is obtained by calculating the quotient of the difference between the current closing price and the high price of *n* periods, and the difference between the high and low prices of *n* periods. The obtained result should then be multiplied by 100. Formula 3 presents the method of calculating the indicator.

$$\%R = \frac{C_z - C_{max}}{C_{max} - C_{min}} * 100 \tag{3}$$

where:

C_z – current closing rate,

C_{max} – maximum rate from n periods,

C_{min} – minimum rate from n periods.

The Williams Percent Range oscillator takes values from -100 to 0. Values close to -100 indicate an oversold zone, while values close to 0 indicate an overbought zone. A buy signal is generated when the oscillator takes values below -80, while a sell signal is generated when they are above -20 (Achelis, 2001).

The DeMarker (DM) indicator, developed by Tom DeMark (1994), compares the periods during which maximum prices are achieved within a selected time frame (see Formula 4).

$$DeM = \frac{SMA\ (DeMax,O)}{SMA(DeMax,O)+SMA\ (DeMin,O)};$$

where:

$DeMax = H\ (i) - H\ (i-1)$ if $H\ (i) > H\ (i-1)$ or

$DeMax = 0$; if $H\ (i) =< H\ (i-1)$ (14)

DeMin = L (i – 1) – L (i) if $L\ (i) < L\ (i-1)$,

DeMin = 0 if L (i) $>= L\ (i-1)$

where:

H (i) – maximum rate of the current period,

L (i) – minimum rate of the current period,

H (i – 1) – maximum rate of the previous period,

L (i – 1) – minimum rate of the previous period,

SMA - simple moving average,

O – number of periods for which the indicator value was calculated.

The oscillator takes values from 0 to 1. Values above 0.7 indicate an overbought market, signaling the potential for a short position or the need to close a long one. Values below 0.3 indicate an oversold market, signaling the opening of a long position or the closing of a short one (DeMark, 1997).

The Stochastic Oscillator developed by George Lane (1984) consists of two lines: %K and %D. The %K line is the main line of the oscillator, and the %D line is a three-period moving average of the %K line. Formula 5 presents the method for calculating the %K line of the Stochastic Oscillator.

$$ST = \frac{C_z - C_{min}}{C_{max} - C_{min}} * 100 \quad (5)$$

where:

C_z – current closing rate,

C_{max} – maximum rate from n periods,

C_{min} – minimum rate from n periods.

The %K and %D lines take values from 0 to 100. %K values above 0.9 indicate that the market is overbought, signaling the potential for a short position or the need to close a long one. On the other hand, values below 0.1 indicate that the market is oversold and signal the opening of a long position or the closing of a short one (Damayanti et al., 2020).

3. Literature Review on the Validity of Technical Indicators for Investing in Stock Market Indices

Many authors have addressed the problem of forecasting stock market index prices using technical indicators, and their research has referenced indices from various geographic locations. This research can be divided into two categories: those referring to European, American, and Asian indices, and those considering indices from other parts of the world.

Detry and Grégoire (2001), in their article, examined the accuracy of technical forecasts using moving averages for stock indices of fifteen European Union countries. Their research covered periods from the inception of specific indices (1965-1993) up to January 1, 1999. They demonstrated that even the most basic technical analysis tools, such as moving averages, enable accurate price forecasting of European stock indices. A similar study was conducted by Fifield, Power, and Sinclair (2005), who tested strategies based on moving averages for indices from eleven European countries in a similar research period (1991-2000). Their results indicated that rates of return on emerging markets (including Greece, Hungary, and Turkey) were characterized by greater predictability than on developed markets (including Germany, France, and the United Kingdom). A study analyzing the accuracy of forecasting the British FS30 index over sixty years was conducted by Chong and Ng (2008). However, MACD and RSI indicators were used to predict the index value in this case. Chong and Ng's results indicated that strategies based on both indicators allowed for obtaining higher rates of return than those resulting from the buy-and-hold strategy. In their research, Trembiński and Stawska

analyzed the accuracy of forecasting the German DAX index using six strategies constructed based on moving averages, oscillators, and trend indicators. They compared their results to those of the buy-and-hold strategy for data from 2015 to 2020. Of the six analyzed strategies, only the one based on the Ichimoku indicator yielded negative rates of return, assuming the worst possible outcome for the investment. At the end of 2019, four technical strategies outperformed the buy-and-hold strategy, and by the end of the first quarter of 2020, all of them had. Trembińska and Stawski (2021) also showed that during periods of increased volatility, technical strategies protected the portfolio against losses to a greater extent than the buy-and-hold strategy. Górska's article, which analyzed, among others, the prices of the WIG 20 Index and the raw material sector indices WIG Spożywczy, WIG Paliwa, and WIG Chemia in the period from March 2009 to July 2011, is relevant to the issue of the accuracy of forecasting stock market index prices using technical indicators (moving averages, oscillators, and the trend indicator – MACD) concerning the Polish market. The article was prepared by Górska (2011), who analyzed, among other things, the prices of the WIG 20 index and the raw material sector indices WIG Spożywczy, WIG Paliwa, and WIG Chemia during the period from March 2009 to July 2011. The buy-and-hold strategy yielded better results than those generated by technical strategies for each of the analyzed indices.

In studies on American stock market indices, the most frequently analyzed rates of return are the S&P 500 Index. Pistole and Metghalchi (2010) compared the accuracy of technical forecasts based on moving averages and the Parabolic SAR and RSI indicators in five-year and seventeen-year periods ending in April 2009. The rates of return generated using the indicators turned out to be higher than those for the buy-and-hold strategy. At the same time, the highest accuracy was achieved using the signals of the Parabolic SAR indicator. The statistical test results confirmed the strategy's statistical significance based on the Parabolic SAR indicator. Paik, Choi, and Vaquer (2024) analyzed the accuracy of signals generated by an algorithm based on indicators such as Williams %R, trading volume, and stochastic oscillator for the S&P 500 Index from 2010 to 2023. The algorithm generated an average annual return of 15.1%, which exceeded the average yearly return from the buy-and-hold strategy. Cohen conducted extensive research comparing technical methods with the buy-and-hold strategy for six U.S. ETFs tracking the S&P 500 (SPY), NASDAQ 100 (QQQ), Russell 2000 (IWM) and the financial (XLF), technology (XLK) and industrial (XLI) sectors, based on data from 1999 to 2018. In the study, he utilized signals generated by six indicators: RSI, stochastic oscillator, MACD, CCI, Money Flow, and Bollinger Bands. The results of Cohen's (2020) research indicated that the signals generated by the CCI and Bollinger Bands proved to be the most accurate, outperforming the buy-and-hold strategy. Cohen also demonstrated that the effectiveness of trading strategies depends on the level of market volatility and the specific combination of technical indicators employed. In some cases, technical strategies proved to be less accurate than the buy-and-hold strategy.

Numerous studies are related to Asian indices. Naved and Srivastava examined the accuracy of signals generated by oscillators, including the stochastic oscillator, RSI, and CCI, for the Indian S&P CNX Nifty 50 index from 2004 to 2014. The results of their research indicated that all three analyzed oscillators generate a similar level of signal accuracy. Slightly better results were observed for the CCI indicator, which outperformed the buy-and-hold strategy by 0.68%. Naved and Srivastava (2015) also demonstrated that the results achieved based on signals generated by individual indicators strongly depend on the period length used for their calculation. A study on the accuracy of RSI indicator signals for the Nifty 50 Index was conducted by Panigrahi, based on data from 2001 to 2020. In this case, the relative strength indicator was used to forecast the beginnings and ends of trends using the 50-50 and 40-60 levels. Panigrahi (2021) demonstrated that the first of the analyzed strategies yields better long-term results, while the second shows better short-term results. Although the rates of return from the analyzed strategies were positive in each year of the analysis, the results were statistically insignificant. Abbasi, Samavi, and Koosh (2020) compared the accuracy of various technical analysis indicators (Bollinger Bands, CCI, Moving Averages, Ichimoku, MACD, RSI, Stochastic Oscillator, and W%R) with the buy-and-hold strategy for ten Iranian stock indices from 2008 to 2018. The hypotheses for each index were tested, stating that there is no significant difference between the results of strategies based on technical analysis indicators and the buy-and-hold strategy over a one-year period. The research results enabled them to reject all hypotheses except the one for the automotive industry index, which showed varying accuracy depending on the specific industry being analyzed. A study was conducted by Christian, Hartini, Jayadi, and Asti to assess the accuracy of technical analysis indicators (moving average, stochastic oscillator, and MACD) for the Indonesian LQ45 Index using data from 2021. The study's results indicated that the stochastic oscillator indications exhibited the highest accuracy (Christian et al., 2022).

The most comprehensive studies on the accuracy of technical indicators were conducted using data from stock market indices across various geographic locations. Chong and Ng (2008), who in their previous studies showed that the RSI and MACD oscillator readings allowed for achieving better results than the buy-and-hold strategy for the British index, conducted another study together with Lie, in which this time they analyzed the accuracy of the above indicators for indices from various geographic locations (Milan Comit General (Italy), S&P/TSX Composite (Canada), DAX 30 (Germany), Dow Jones (USA), Nikkei 225 (Japan) based on data from 1976 to 2002. Chong, Ng, and Lie's (2014) research results indicated that strategies based on RSI and MACD oscillators generate different results depending on the market studied. In the case of the Italian and American indices, the studied trading rules outperformed the buy-and-hold strategy. In contrast, the classic strategy yielded higher returns for the Japanese index. Partially consistent conclusions were obtained by Cohen and Cabiri (2015), who examined the accuracy of signals generated by indicators such as RSI, MACD, Parabolic SAR, and stochastic oscillator in the years 2007-2012 for the following indices:

Dow Jones (the USA), FTSE 100 (the United Kingdom), Nikkei 225 (Japan), and TA100 (Israel). The results of their research indicated that the highest accuracy was characteristic of signals generated by the RSI indicator, which outperformed the buy-and-hold strategy for the following indices: American, British, and Japanese. The results for the American and British indices were consistent, whereas those for the Japanese index diverged from the results obtained by Chong, Ng, and Lie (2014). A similar study, which examined the accuracy of technical analysis indicators for the Dow Jones (the USA), Euro Stoxx 50 (Europe), and Nikkei 225 (Japan) indices from May 1, 2018, to May 1, 2020, was conducted by Teresiene and Aleksynaite. In this case, in addition to the RSI, MACD, and PSAR indicators, moving averages, ADX, VPT, MFI, and A/D were also used. Teresiene and Aleksynaite (2020) noticed that technical analysis indicators are characterized by a similar level of accuracy in different markets and that the signals generated by the indicators are consistent with each other in the case of similar price movements, e.g., after the declines caused by the beginning of the COVID-19 pandemic, the MACD, moving averages, PSAR, ADX, VPT, and A/D indicators denoted a buy signal. The RSI indications turned out to be neutral. Paik, Choi, and Vaquero (2024) conducted research proposing a model based on W%R indicators and the stochastic oscillator, utilizing data from ETF funds that reflect the values of the American S&P 500 index and the Korean MSCI Korea index from 2010 to 2022. The results of their research indicated that the proposed model outperformed the classic buy-and-hold strategy, achieving approximately 80% accuracy and generating an average of 1.5 transactions per year.

Table 1 summarizes the results of previous research on the accuracy of technical indicators for investing in stock market indices.

Table 1.
Summary of the results of previous research on the accuracy of technical indicators for investing in stock market indices

Author and year of publication	Index / ETF (country)	Indicators used	Main conclusions
Detry, Grégoire (2001)	Stock exchange indices from 15 European Union countries	Moving averages	The simplest technical analysis tools such as moving averages allow for accurate forecasting of European stock indices.
Fifield, Power, Sinclair (2005)	Hex (Finland), CAC-40 (France), DAX (Germany), Athens SE (Greece), BUX (Hungary), ISEQ (Ireland), MIB Storico (Italy), BVL (Portugal), Madrid SE (Spain), ISE National (Turkey), FTSE All Share (UK)	Moving averages	Emerging markets are characterized by greater predictability of returns than developed markets.
Chong, Ng (2008)	London Stock Exchange FT30 (UK)	MACD, RSI	Strategies based on RSI and MACD indicators allow for higher rates of return in most cases than the "buy and hold" strategy.

Cont. table 1.

Górska (2011)	WIG 20, WIG Food, WIG Fuels and WIG Chemistry (Poland)	Moving Averages, MACD, Momentum, CCI	In the case of all analysed indices, the "buy and hold" strategy generated higher rates of return than strategies based on technical indicators.
Trembiński, Stawska (2020)	DAX (Germany)	Moving Averages, RSI, CCI, Stochastic Oscillator, Ichimoku, Parabolic SAR, MACD, Bollinger Bands	Strategies based on technical indicators outperformed the buy-and-hold strategy in most cases, and during periods of increased volatility they protected the portfolio against losses to a greater extent.
Pistole, Metghalchi (2010)	S&P500 (US)	Moving Averages, Parabolic SAR, RSI	Moving averages and technical indicators PSAR and RSI both in the short (5 years) and long (17 years) periods outperform the "buy and hold" strategy. The highest statistically significant results were obtained in the case of the PSAR strategy.
Paik, Choim, Vaquero (2024)	S&P 500 (US)	Stochastic Oscillator, Williams %R, Trading Volume	The algorithm built on the basis of three technical indicators allowed to generate an average annual rate of return on the S&P500 index in the analyzed period at the level of 15.1%.
Cohen (2020)	S&P 500, NASDAQ 100, Russell 2000, XLF, XLK, XLI (US)	RSI, Stochastic Oscillator, MACD, CCI, MFI, Bollinger Bands	The signals generated by the CCI indicator and Bollinger Bands proved to be the most accurate, outperforming the "buy and hold" strategy. The effects of trading strategies depend on the level of market volatility and the combination of technical indicators adopted. In some cases, technical strategies proved to be less accurate than the "buy and hold" strategy.
Naved, Srivastava (2015)	S&P CNX Nifty 50 (India)	Stochastic Oscillator, RSI, CCI	The CCI indicator generated the highest results among the indicators tested. The result achieved on the basis of signals generated by individual indicators is strongly dependent on the length of the period used for its calculation.
Ebrahim, Samavi, Koosha (2020)	10 indexes of the Tehran Stock Exchange (Iran)	Bollinger Bands, CCI, Moving Averages, Ichimoku, MACD, RSI, Stochastic Oscillator, Williams %R	The validity of technical analysis strategies varies depending on the industry being analyzed.
Panigrahi (2021)	NIFTY 50 (India)	RSI	The 50-50 strategy is characterized by greater accuracy in the long term and the 60-40 in the short term. The rates of return from both technical strategies in each year of the study period turned out to be positive.
Christian, Hartini, Jayadi, Asti (2022)	LQ45 (Indonesia)	Moving Averages, Stochastic Oscillator, MACD	The stochastic oscillator readings were characterized by the highest accuracy.

Cont. table 1.

Chong, Ng, Lie (2014)	Milan Comit General (Italy), S&P/TSX Composite (Canada), DAX 30 (Germany), Dow Jones (USA), Nikkei 225 (Japan)	MACD, RSI	Strategies based on RSI and MACD generate varied results depending on the market studied. In the case of the Italian and American indices, the trading rules studied outperformed the buy-and-hold strategy, while in the case of the Japanese index, the classic strategy allowed for generating higher rates of return.
Cohen, Cabiri (2015)	Dow Jones (USA), FTSE 100 (UK), Nikkei 225 (Japan), TA100 (Israel)	RSI, MACD, Para-bolic SAR, Stochastic Oscillator	The highest accuracy was achieved by signals generated by the RSI indicator, which exceeded the results of the "buy and hold" strategy for the American, British and Japanese indices in five out of six years examined.
Teresienė, Aleksynaite (2020)	Dow Jones (USA), Euro Stoxx 50 (Europe), Nikkei 225 (Japan)	MACD, Moving Averages, RSI, Para-bolic SAR, ADX, VPT, MFI and A/D	Technical analysis indicators are characterized by a similar level of accuracy in different markets. In the case of similar price movements, identical signals appear in different markets.
Paik, Choi, Vaquero (2024)	S&P 500 (USA), MSCI Korea (South Korea)	William %R, stochastic oscillator	The proposed trading model was characterized by an accuracy level of 80% and exceeded the results of the "buy and hold" strategy.

Source: own study.

Based on the literature review, it is worth noting that the accuracy of signals generated by the RSI indicator was analyzed most often, in as many as 10 cases. Other frequently used indicators include MACD (9), moving averages (8), stochastic oscillator (7), CCI (5), and Parabolic SAR (4). The accuracy of technical analysis indicators was most often examined for the following indices: the S&P 500 (four times), the Nikkei 225, and the Dow Jones (three times each). Indices from a total of 27 countries and regions were examined; in 11 cases, they were American indices; in 10 cases, Iranian (the results of research on Iranian indices were presented in a separate article (Abbasi, 2020)); and in four cases, the indices of Germany, the United Kingdom, and Poland. In turn, considering the continents from which the individual indices originated, most often, in 36 cases, they were European indices (54.55% of all those examined), in 18 cases (27.27%) Asian, and in 12 cases (18.18%) North American. Based on the above analysis, it is worth noting that, in the literature, there is a limited number of studies comparing the accuracy of technical analysis indicators across markets from different regions of the world, with a notable focus on individual continents. In the case of cross-sectional studies, they primarily refer to indices from, at most, several countries, which represents an interesting research gap. It is also worth noting that studies on the accuracy of indicators for investments in indices are typically characterized by short research periods of several years or a few dozen years, omitting many years of the indices' existence, which is also an example of a research gap.

4. Research Methodology

The research strategy employed in this article is quantitative in nature. This research involves testing hypotheses (Czakon, 2016), and the data analysis aims to reveal or confirm the relationships between variable spresent in the studied investment strategies (Sułkowski et al., 2001).

Quantitative research was conducted from September 2024 to December 2024 using an MS Excel spreadsheet as a research tool. The study aimed to assess the effectiveness of using existing investment strategies, such as buy-and-hold and classic indicators, compared to newly defined avant-garde indicators, and to investigate the relationships between the use of all studied strategies and the return obtained from investing in a given stock index.

The study was designed as a data table using MS Excel, which was supplemented with values obtained from a website (Stooq.pl, 2025, March 15) containing historical data on global stock market indices. The database contained historical quotations of 63 global stock market indices from all continents, spanning from the beginning of each index to December 31, 2023, as this date marked the lastday of the completed full calendary earat the time of the study.

The computational stage of the research process was conducted using an MS Excel spreadsheet and was divided in to six parts.

- The first part of the study involved arranging the data for each studied indices in a separate table, clearly distinguishing the quotation date, opening price, high estsession price, lowe stsession price, and closing price.
- In the second part of the study, for each of the studiem indices, the values of verified classic indicators, such as RSI, CCI, W%R, DM, and ST, were calculated for each trading day. Based on this, potential days of purchase and sale of the security were determined for the selected indices.
- In the third part, days in which a signal with the same purpose was repeated were eliminated, allowing for subsequent signals in the buy-sell, buy-sell, etc. arrangement. If the last remaining signal was a buy, the sale price from the day of the previous quotations in the examined period was used. Then, all ordered signals were summed up for the adopted research period to obtain the final investment result for each classic indicator examined separately.
- In the fourth part of the study, the system of operation for new avant-garde indicators was defined, wchich consisted of using signals generated by all the classical indicator sstudied but in the opposite direction. The moment of purchase in this casemeant sale, and the sell signal defined purchase. In this way, five new indicators were obtained, which were named RSI_A, CCI_A, W%R_A, DM_A, and ST_A. The investment results achieved using the newly defined indicators were summarized.

- In the fifth part of the study, investment results were calculated using the standard buy-and-hold strategy, where it was assumed that the first day of quotation of each of the examined indices is the buy date, and December 31, 2023, i.e., the last day of the research period, is the sell date.
- In the last, sixth part of the study, the returns on investment were compared Rusing individual strategies, i.e., classic indicators, new avant-garde indicators, and the buy-and-hold strategy. It should be emphasized that the comparison of values consisted in recognizing the highest of them in all the strategies examined where, if the highest return on investment value was recognized in the group of classic indicators, the classic indicators were marked as the most economically advantageous method to use, if the highest return value occurred in the group of avant-garde indicators, they were marked as the most effective. If the value of the buy-and-hold strategy turned out to be the best, it was named the best strategy. The average values of the return on investment for the group of five classic indicators and five avant-garde indicators were also verified and compared with the buy-and-hold strategy. As before, the most economically advantageous method was determined to have the highest return on investment.

The analysis of the firstst age of the study's results, conducted using data from global stock market indices and an MS Excel spreadsheet, was subjected to statistical testing using the GRETL program.

- First, a summary specified which specific global stock market indices were examined.
- Next, tests were conducted to confirm or refute the hypotheses adopted in this article.
- Finally, synthetic results were presented to illustrate the effectiveness of the individual investment methods. For statistical verification, the probability of the first type of error was assumed to be 0.05 (alpha = 0.05).

To summarize, the study was quantitative in nature and conducted using historical data from 63 globalstock market indices. The analysis compared the effectiveness of classical technical indicators, newly defined avant-garde indicators, and the buy-and-hold strategy. Data processing was carried out in MS Excel, and statistical verification was performer using the GRETL program with a significance level of $\alpha = 0.05$. The results enabled an assessment of the effectiveness of the individual investment strategies.

5. Verification of Phenomena Influencing Strategies for Economically Advantageous Investment Results in Global Stock Market Indices

The study included 63 stock market indices, encompassing 32 indices from the European continent, 15 indices from the Asian continent, two indices from Australia, nine indices from North America, three indices from South America, one index from the African continent,

and one index covering the whole world. Knowing the characteristics of the information studied regarding global stock market indices and the conduct of the individual research parts, it was reasonable to analyze the results correctly. The first part verified the occurrence of selected phenomena that condition avant-garde indicators as the most economically advantageous when investing in global stock market indices included in the research hypotheses. The first test of the hypotheses was conducted using the proportion test, which involved comparing the number of more advantageous investment results obtained with avant-garde indicators with those obtained with classic indicators and the buy-and-hold strategy across 63 global stock market indices.

Based on the preliminary analysis of the results obtained using MS Excel software, it was expected that the results would be more economically advantageous for using avant-garde indicators. Therefore, a one-sided critical region was adopted for the analysis. The analysis results, employing the proportion test to assess the occurrence of a given phenomenon in the examined stock exchange indices, are presented in Table 2.

Table 2.
Proportion test analysis of the assessment of the occurrence of a given phenomenon in the examined stock exchange indices.

Assessment of the occurrence of a given phenomenon	**N**	**WSR**	**WSP**	**Z**	**P**
The use of avant-garde indicators presents higher return values than the use of classic indicators.	63	0,857143	0,142857	16,2019	2,446e-59*
The use of vanguard indicators shows higher return values than the use of a buy and hold strategy	63	0,68254	0,31746	6,22515	2,405e-10*

N - number of observations, WSR - structure index in the sample of positive answers, WSP - structure index in the sample of negative answers, z - value of the proportion test, p - significance level.

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The analysis of proportions for the first phenomenon, using avant-garde indicators as a solution presenting higher return values than classic indicators, showed that the hypothesis of equality of proportions should be rejected (z = 16.2019, p = 2.446e-59*). The hypothesis stating that there are more results regarding the use of avant-garde indicators as a solution that presents higher return values should be accepted.

The analysis of proportions for the secondo phenomenon, using avant-garde indicators as a solution that presents higher return values than the buy-and-hold strategy, showed that the hypothesis of proportione quality should be rejected (z = 6.22515, p = 2.405e-10). The hypothesis stating that there are more results regarding the use of avant-garde indicators as a solution that presents higher return values should be accepted.

In summary, both analyses regarding the use of avant-garde indicators showed that they provide higher return values than classical indicators and the buy-and-hold strategy. **Significantly more** results demonstrating these higher return values were obtained by

employing avant-garde indicators. This fact allowsus to akcept Hypothesis H1: **"The use of an investment strategy using the developer avant-garde indicators is more economically advantageous than the use of existing classic indicators for the main world stock exchange indices"**, and it also confirms Hypothesis H2: **"The use of an investment strategy using the developed avant-garde indicators is more economically advantageous than the use of the buy-and-hold strategy for the leading world stock exchange indices".**

The subsequent analysis aimed to verify Hypothesis H3, chich states that the use of avant-garde indicators shows the highest accuracy regardless of geographic location.

To verify, the stock market indices under study were divided in to six subgroups with different geographic distributions, such that they represented allcontinents with the lar gest number of studiem indices separately, and the remaining continents were combined into a separate subgroup. In this way, three continents were identified, representing the largest number of indices under study: Europe, Asia, SouthAmerica, and NorthAmerica. The remaining subgroups represented the following: all other continents excluding Europe, all other continents excluding Asia, and all other continents excluding the Americas. It should be emphasized that the number of indices dictated the above division on each of the individual continents, where if the number of indices under study presented a value below 10, the given continent was not distinguished as a separate subgroup due to the small amount of data (below 15% of the en tire population). The exception was the continent of North America and South America, where, to obtain the minimum amount of data, the results of both continents were summarized due to similarities resulting from national conditions.

To verify Hypothesis H3, a *t*-test was conducted first. This allowed us to determine whether there are significant differences in the application of the studied investment methods between the designated subgroups representing the continents with the largest number of studied indices. It should be emphasized that, despite dividing the studied stock exchange indices in to smaller subgroups and thus reducing the number of samples within a given subgroup. The literature (Meek et al., 2007) allows for the use of the *t*-test for small sample sizes. The results of the *t*-test analysis, assessing differences in the number of results that are more economically advantageous for the applied investment methods in the studiem stock exchange indices, categorized into Europe and the remaining continents, are presented in Table 3.

Table 3.
T-test analysis of the assessment of differences in the number of economically more advantageous results for the investment methods used in the examined stock exchange indices, divided into Europe and other continents.

	Europe			**Other continents without Europe**				
Evaluation of differences in the number of results more favorable for the investment methods used	**N**	**M**	**Q**	**N**	**M**	**Q**	t	p
Investment strategies	32	10,67	10,97	31	10,33	8,02	0,140058	0,445

N - number of observations, M - sample mean, Q - standard deviation, t - test value, p - significance level

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The *t*-test analysis to determine whether there are significant differences in the results of the European indices and those of the other continents, excluding Europe, regarding the number of results more economicallyadvantageous for the applied investment methods, yielded a *p*-value of 0.445 (t = 0.140058). Therefore, the hypothesis should be accepted that the results of the European indices and the other continents **do not differ significantly**. The results of the *t*-test analysis assessing differences in the number of results that are more economicallyadvantageous for the applied investment methods in the examined stock exchange indices, divided into North America, South America, and all other continents, excluding the Americas, are presented in Table 4.

Table 4.
T-test analysis of the assessment of differences in the number of economically more advantageous results for the investment methods used in the examined stock exchange indices, divided into North and South America and other continents, excluding the Americas

	North and South America			**Other continents excluding the Americas**				
Other continents excluding the Americas	**N**	**M**	**Q**	**N**	**M**	**Q**	T	p
Investment strategies	12	4	3	51	17	17,78	-2,50974	0,007376*

N - number of observations, M - sample mean, Q - standard deviation, t - test value, p - significance level.

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The *t*-test analysis to determine whether there are significant differences in the results of the American indices and those of the other continents, excluding the Americas, regarding the number of more economically advantageous results for the applied investment methods showed a considerable difference (t = -2.50974, p = 0.007376*). Therefore, the hypothesis should be accepted that the results of the American indices and the other continents, excluding the Americas, **differ significantly**. The results of the *t*-test analysis, assessing differences in the number of more economically advantageous outcomes for the applied investment strategies in the examined stock exchange indices, are presented in Table 5, divided into Asia and the other continents excluding Asia.

Table 5.
T-test analysis of the assessment of differences in the number of economically more advantageous results for the applied investment strategies in the examined stock exchange indices, divided into Asia and other continents, excluding Asia

	Asia			**Other continents excluding Asia**				
Evaluation of differences in the effectiveness of the investment strategies used	**N**	**M**	**Q**	**N**	**M**	**Q**	T	p
Investment strategies	15	5	7	48	16	12	-3,36402	0,0006661*

N - number of observations, M - sample mean, Q - standard deviation, t - test value, p - significance level.

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The *t*-test analysis to determine whether there are significant differences in the results of the Asian indices and those of the other continents excluding Asia regarding the number of results that are more economically advantageous for the applied investment strategies showed a considerable difference (t = -3.36402, p = 0.0006661*). Therefore, the hypothesis should be accepted that the results of the Asian indices **differ significantly** from those of the other continents.

In summary, the *t*-test revealed no significant differences in the number of more economically advantageous results obtained for the applied investment strategies across European indices and all other continents. In the groups of American indices and different continents, as well as Asian indices and other continents, the *t*-test revealed significant differences in the number of economically advantageous results obtained for the applied investment strategies. Due to the diversified results in the area of the designated subgroups, it was justified to conduct the second part of the analysis, which consisted of assessing the significance of the application of individual investment strategies separately for each of these subgroups to determine whether the application of avant-garde indicators shows the highest accuracy regardless of geographic location.

The analysis was conducted based on the proportion test. The test determined whether the number of results more economically advantageous for applying individual investment strategies constitutes a significant majority of all the results obtained for indices in designated geographic subgroups. Because in the area of division of indices into geographic subgroups, we cannot determine whether the strategy shows a right- or left-sided direction of changes, a two-sided critical region was applied.

Since, based on the *t*-test results, the European indices were expected to yield the same results for individual investment strategies as the entire studied group (all other continents, excluding Europe), the first analysis to be carried out was amateriality analysis of applying individual investment strategies to the European continent (see Table 6).

Table 6.
Proportion test analysis of the assessment of the investment strategies used for the European continent

Assessment of the application of individual investment strategies	Assessment of the application of individual investment strategies				
	N	WSR	WSP	Z	p
B&H Strategy	32	0,21875	0,5	-3,18198	0,001463*
Strategy Classic Indicators	32	0,0625	0,5	-4,94975	7,431e-07*
StrategyVanguardIndicators	32	0,71875	0,5	2,47487	0,01333*

N - number of observations, WSR - structure index in the sample of positive answers, WSP - structure index in the sample of negative answers, z - value of the proportion test, p - significance level

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The analysis of proportions for the assessment of the applied investment strategies for the European continent indicated that for one strategy (Avant-Garde Indicator Strategy), which showed (z = 2.47487, p = 0.006664) where the *z*-value revealed a right-sided critical

region, it is reasonable to reject the hypothesis that the proportion of the sample of economically advantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the proportion of economically advantageous results for the Avant-Garde Indicator Strategy is significantly greater than 50% of all results should be accepted.

For the two remaining strategies (Buy-and-Hold Strategy, Classic Indicators Strategy), which showed (z = -3.18198, p = 0.0007314) and (z = -4.94975, p = 3.715e-07) respectively, where the *z*-values revealed the left-sided critical region, it is reasonable to reject the hypothesis that the sample proportion of more economically advantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the sample proportion of more economicallyadvantageous results for the Buy-and-Hold Strategy and the Classic Indicator Strategy is significantly smaller than 50% of all results should be accepted.

In the American and all other continental indices, as well as inthe Asian and all other continental indices, the *t*-test revealed significant differences in the number of results obtained, which were more economicallyadvantageous for the applied investment strategies. Therefore, the significance of applying individual investment strategies was analyzed separately for each group. The results of the analysis, using the proportion test to assess the applied investment strategies for the American and all other continents, are presented in Table 7.

Table 7.
Proportion test analysis of the evaluation of the investment strategies used for the American and other continents

Assessment of the application of individual investment strategies	American continents					Other continents excluding the Americas				
	N	WSR	WSP	z	P	N	WSR	WSP	z	p
B&H Strategy	12	0,583	0,5	0,577	0,5637	51	0,216	0,5	-4,06	0,001279*
Classic Indicators Strategy	12	0,083	0,5	-2,887	0,003892*	51	0,058	0,5	-6,30	2,952e-10*
Strategy Vanguard Indicators	12	0,333	0,5	-1,155	0,2482	51	0,73	0,5	3,22	0,0006395*

N - number of observations, WSR - structure index in the sample of positive answers, WSP - structure index in the sample of negative answers, z - value of the proportion test, p - significance level.

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The analysis of proportions for the evaluation of the applied investment strategies for the American continents showed that for one strategy (Classic Indicator Strategy), which shows (z = -2.887, p = 0.003892) where the *z*-value revealed the left-sided critical region, it is reasonable to reject the hypothesis that the proportion of the sample of the number of more economicallyadvantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the proportion of the sample of more economically advantageous results for the Classic Indicator Strategy is significantly smaller than 50% of all results should be accepted.

For the remaining two strategies in the group of American continents, Buy-and-Hold Strategy and Avant-Garde Indicator Strategy, the results showed (z = 0.577, p = 0.5637) and (z = -1.155, p = 0.2482), respectively, it is reasonable to accept the hypothesis that the sample proportion of the number of more economically advantageous results for individual financial strategies constitutes 50% of the results.

In the group of the remaining continents, two investment strategies (Buy-and-Hold Strategy and Classic Indicator Strategy), where the *z*-values revealed a left-sided critical region, showed (z = -4.06, p = 0.001279) and (z = -6.30, p = 2.952e-10), respectively, which justifies the rejection of the hypothesis that the sample proportion of more economically advantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the sample proportion of more economically advantageous results for the Buy-and-Hold Strategy and the Classic Indicator Strategy is significantly smaller than 50% of all results should be accepted.

The third investment strategy in the group of other continents for the Avant-Garde Indicator Strategy showed (z = 3.22, p = 0.006395), where the *z*-value revealed a right-sided critical region, it is reasonable to reject the hypothesis that the proportion of the sample of the number of more economicallyadvantageous results for individual financial strategies constitutes 50% of the results. The hypothesis, which states that the proportion of the sample of more economically advantageous results for the Avant-Garde Indicator Strategy is significantly greater than 50% of all results, should be accepted. The results of the proportion test analysis, assessing the investment strategies employed for the Asian continent and all other continents excluding Asia, are presented in Table 8.

Table 8.
Proportion test analysis of the evaluation of the investment strategies used for the Asian continent and other continents except Asia

Assessment of the application of individual investment strategies	Asian continent					Other continents excluding Asia				
	N	WSR	WSP	Z	P	N	WSR	WSP	z	p
B&H Strategy	15	0,133	0,5	-2,840	0,004509*	48	0,333	0,5	-2,309	0,02092*
Strategy Classic Indicators	15	0	0,5	-	-	48	0,083	0,5	-5,774	7,764e-09*
Strategy Vanguard Indicators	15	0,866	0,5	2,840	0,002254*	48	0,583	0,5	1,155	0,2482

N - number of observations, WSR - structure index in the sample of positive answers, WSP - structure index in the sample of negative answers, z - value of the proportion test, p - significance level.

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The analysis of proportions for the assessment of the applied investment strategies for the Asian continent indicated that for the Strategy of Avant-Garde Indicators, which showed (z = 2.840, p = 0.002254) where the *z*-value revealed a right-sided critical region, it is reasonable to reject the hypothesis that the proportion of the sample of the number of more economically advantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the proportion of the sample of more economically advantageous results for the Strategy of Avant-Garde Indicators is significantly greater than 50% of all results should be accepted.

For the next strategy under study, the Buy-and-Hold Strategy, which yielded a *z*-value of -2.840 (p = 0.004509), where the *z*-value indicated a left-sided critical region, it is reasonable to reject the hypothesis that the sample proportion of more economically advantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the sample proportion of more economicallyadvantageous results for the Buy-and-Hold Strategy is significantly less than 50% of all results should be accepted.

For the last strategy examined (Classic Indicator Strategy), the structure indicator in the sample is 0, which means that this feature was not present in the examined sample.

In the second studied group, all other continents without Asia, the analysis of proportions for the assessment of the applied investment strategies for the Asian continent indicated that for two strategies (Buy-and-Hold Strategy and Classical Indicator Strategy), which showed (z = -2.309, p = 0.02092) and (z = -5.774, p = 7.764e-09), respectively, the *z*-values revealed the left-sided critical region, which means that it is justified to reject the hypothesis that the proportion of the sample of the number of more economically advantageous results for individual financial strategies constitutes 50% of the results. The hypothesis that the proportion of sample results more economically advantageous for the Buy-and-Hold Indicators Strategy and the Classical Indicators Strategy is significantly smaller than 50% of all results should be accepted.

For the Avant-Garde Indicators investment strategy in the group of all other continents excluding Asia, the analysis showed (z=1.155, 0.2482), which indicated a right-sided critical region and there was no basis to reject the hypothesis that the sample proportion of more economically advantageous results for individual financial strategies constitutes 50% of the results.

After conducting both parts of the analysis to confirm the third hypothesis presented in this article, which investigates whether the use of avant-garde indicators yields the highest accuracy regardless of geographic location, a synthetic summary of the results is presented in Table 9.

Table 9.
Summary of analyses using the proportion test to assess the investment strategies used for individual groups of continents

Summary of the application of individual investment strategies	European continent	American continents	Other continents excluding the Americas	Asian Continent	Other continents excluding Asia
B&H Strategy	WKE < 50%	WKE = 50%	WKE < 50%	WKE < 50%	WKE < 50%
Strategy Classic Indicators	WKE < 50%	WKE < 50%	WKE < 50%	No feature in the sample	WKE < 50%
StrategyVanguardIndicators	WKE > 50%	WKE = 50%	WKE > 50%	WKE > 50%	WKE = 50%

WKE - economicallymoreadvantageousresults.

Source: Ownstudybased on a study of rates of return on globalstock exchange indicesusing the GRETL program.

The analysis showed that applying the Buy-and-Hold and Classic Indicator investment strategies yields significantly fewer economically advantageous results for practically all the groups of continents examined. The exceptions are the American continents, where the Buy-and-Hold Strategy yielded similar results to the Avant-Garde Indicator Strategy, with the number of economically advantageous results falling within 50% of the results. For the Classic Indicator Strategy for the Asian continent, there is no feature corresponding to the sample.

Applying the Avant-Garde Indicators investment strategy enabled us to achieve a significantly higher number of more economically advantageous results for the three examined groups of continents: the European continent, all other continents excluding the Americas, and the Asian continent. For the remaining groups of continents – the American continents and all other continents excluding Asia – the application of the Avant-Garde Indicator strategy yielded a number of economically advantageous results, accounting for approximately 50% of the total results. However, it should be remembered that all other continents, excluding the Asian group, include the indices of the American continents, which may affect the outcome of this entire group by lowering the alpha value due to the higher number of economically advantageous results in the Avant-Garde Indicators investment strategy group. Therefore, another proportion test was conducted to confirm whether the indices for the American continent improve the results of the subgroup of other continents, excluding Asia, and whether they demonstrate the same properties as all subgroups except those from the American continents (see Table 10).

Table 10.
Proportion test analysis of the assessment of the investment strategies used for the remaining continents, excluding Asia and the Americas

Assessment of the application of individual investment strategies	Other continents excluding Asia and the Americas				
	N	WSR	WSP	Z	p
B&H Strategy	48	0,25	0,5	-3	0,0027*
Strategy Classic Indicators	48	0,0834	0,5	-4,9992	5,757e-07*
StrategyVanguardIndicators	48	0,667	0,5	2,004	0,04507*

N - number of observations, WSR - structure index in the sample of positive answers, WSP - structure index in the sample of negative answers, z - value of the proportion test, p - significance level

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

As expected, additional proportion analysis for assessing the investment strategies used for the remaining continents, excluding Asia and the Americas, revealed the same trend as all the examined groups of continents, except for the American continents.

In summary, the avant-garde indicator strategy generated a significantly higher number of economically favorable outcomes compared to the other strategies applied, with the exception of the American continents, where both the avant-garde indicator strategy and the buy-and-hold strategy yielded similarly beneficial results. This outcome partially confirms Hypothesis H3, which assumes the geographical robustness of avant-garde indicators, while also extending it by suggesting that outside the Americas, the effectiveness of avant-garde indicators is clearly superior.

Although Hypothesis H3 posits the universal applicability of this approach, the results revealed notable regional differences, particularly across the Americas. A possible explanation for these discrepancies may lie in macroeconomic factors (e.g., interest rate levels, inflation), geopolitical conditions (e.g., political stability, market regulations), and structural characteristics (e.g., dominance of specific sectors in regional indices). For instance, American indices are known for their high informational efficiency and liquidity, which may limit the advantage of technical strategies. Future research should consider incorporating these variables as additional dimensions of analysis to better understand the contextual limitations and strengths of avant-garde indicators in global markets.

6. Summary and Discussion

The conducted research has shown that the application of an investment strategy using the developed Avant-Garde Indicators is more economically advantageous than the application of the existing Classic Indicators and the Buy-and-Hold Strategy for the leading world stock market indices, with the proviso that for the American continents the Avant-Garde Indicator Strategy brings similar results to the Buy-and-Hold Strategy. However, it is worth noting that five new indicators were identified in the Avant-Garde Indicator Strategy, and their highest results were analyzed for each of the examined indices. At this point, the question arises of whether significantly more economically advantageous results would be obtained when selecting any of the five newly developed indicators that are part of the Avant-Gard Indicator Strategy than when using the other examined strategies.

In anattempt to answer this question, another analysis was conducted, using the proportion test, which consisted in comparing the number of more favorable investment results using avant-garde indicators to the number of more favorable investment results using classic indicators and the buy-and-hold strategy, with the proviso that the average values of return on investment in the group of five classic indicators and the group of five avant-garde indicators

would be adopted for the study, and not the highest values in the group as hadbeen the case in earlier analyses (seeTable 11).

Table 11.
Proportion test analysis of the assessment of the occurrence of a given phenomenon in the examined stock exchange indices after changing the method of selecting the most favorable value in the group of Avant-Garde and Classic Indicators

Assessment of the occurrence of a given phenomenon	N	WSR	WSP	Z	p
The average return value of the Avant-Garde Indicators group is higher than the average return value of the Classic Indicators group	63	0,904762	0,095238	21,8891	1,65e-106
The average return of the Vanguard Indicators group is higher than the return of the "buy and hold" strategy	63	0,460317	0,539683	-1,26388	0,1031

N - number of observations, WSR - structure index in the sample of positive answers, WSP - structure index in the sample of negative answers, z - value of the proportion test, p - significance level.

Source: Own study based on a study of rates of return on global stock exchange indices using the GRETL program.

The analysis of proportions for the first phenomenon – the average return value of the Avant-Garde Indicators being higher than that of the Classic Indicators – showed that the hypothesis of equality of proportions should be rejected (z = 21.8891, p = 1.65e-106). The hypothesis that the average return value of the Avant-Garde Indicators group is higher than that of the Classic Indicators group should be accepted.

The analysis of proportions for the second phenomenon – the average return value of the Avant-Garde Indicator Group being higher than the average return value of the buy-and-hold strategy – showed that there is no basis for rejecting the hypothesis of equality of proportions (z = -1.26388, p = 0.1031*).

To summarize, the analysis comparing the average return value from the group of Avant-Garde Indicators with that from the group of Classic Indicators revealed significantly more results with a higher average return value for the Avant-Garde indicators. On the other hand, for the analysis concerning the average return value from the group of Avant-Garde Indicators, which is higher than that of the Buy-and-Hold Strategy, significantly more results with a higher average return value were obtained. Therefore, the conclusion is that by selecting any indicator from the examined group of Avant-Garde Indicators, we will, on average, receive a higher return on investment than by choosing an indicator from the group of Classic Indicators. In contrast, the obtained return value will not exceed that of the Buy-and-Hold Strategy.

This fact suggests that to achieve the highest possible return on investment using the examined investment strategies, it is necessary to analyze historical data for a given index across all five indicators from the group of newly developed Avant-Garde Indicators and select the most profitable.

The results of the conducted research also encourage further exploration and investigation of potential relationships based on the newly identified Avant-Garde Indicators, which may ultimately lead to the development of a single, universal indicator that consistently demonstrates the highest economic efficiency of the investment under given conditions.

It should also be noted that the results of this research constitute a breakthrough in terms of the universal nature of applying investment strategies to various geographic locations, as a considerable number of authors compare the accuracy of technical analysis indicators for individual continents or, in the case of cross-sectional studies, narrow it down to only a few countries.

In addition, previous studies are typically characterized by short research periods of several years or less, often omitting many years of the indices' existence. In contrast, the research conducted in this article treats the data of global stock exchange indices holistically. It analyzed data available from the beginning of each of them, which allowed us to neutralize the effects of occasional fluctuations in quotations related to the specific economic situation of a given period. Thanks to this, it was possible to increase the transparency of the results, eliminating the risk of falsifying the actual research result.

It is also worth noting that the research on the accuracy of indicators for investing in indices presented by other researchers is mainly based on existing technical analysis indicators, contrary to the research presented in this article, which focuses on searching for new methods that allow for the development of even more effective ways of investing in stock market indices than those known so far. Thus, taking into account the fact that many researchers whose research results are cited in this article present the superiority of technical analysis methods over the buy and hold strategy, this research presents for the first time the superiority of the newly developed technical analysis method, which is the Avant-Garde Indicators over the Classic Indicators for all geographic regions.

It should be emphasized, however, that the conducted study has certain limitations resulting from the omission of trans action costs, price slippage, and liquidity constraints, all of which can significantly affect the actual performance of investment strategies based on technical signals. A particularly important aspectis the frequent positions witching generated by some indicators, which may lead to increased operational costs and, consequently, reduce the effectiveness of the strategy under real market conditions. Therefore, future research should consider these factors by implementing trans action simulations or analyzing data from markets with varying levels of liquidity, which would allow for a more comprehensive understanding of the practical potential and limitations of the strategies under examination.

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Appendix

List of global stock market indices examined

LP	Ticker	Index	Country	Continent	Beginning of the research period
1	^AOR	ALL ORDINARIES	Australia	Australia	01.01.1875
2	^HSI	HANG SENG	Hong Kong	Asia	24.11.1969
3	^JCI	JCI	Indonesia	Asia	04.04.1983
4	^KLCI	KLCI	Malaysia	Asia	03.01.1977
5	^KOSPI	KOSPI	South Korea	Asia	04.01.1980
6	^NKX	NIKKEI225	Japan	Asia	01.03.1914
7	^NZ50	NZX50	New Zealand	Australia	03.01.2001
8	^PSEI	PSEI	Philippines	Asia	02.01.1986
9	^SET	SET	Thailand	Asia	30.04.1975
10	^SHBS	SSE B-SHARE	China	Asia	04.01.2000
11	^SHC	SSE COMP	China	Asia	19.12.1990
12	^SNX	SENSEX	India	Asia	03.04.1979
13	^STI	STRAITS TIMES	Singapore	Asia	28.12.1987
14	^TWSE	TAIEX	Taiwan	Asia	05.01.1995
15	A5.C	ATX INDEX	Austria	Asia	11.11.1992
16	^AEX	AEX	Netherlands	Europe	03.01.1983
17	^ATH	ATHEX COMP	Greece	Europe	02.01.1987
18	^BEL20	BEL20	Belgium	Europe	02.01.1991
19	^BET	BET	Romania	Europe	31.10.2000
20	^BUX	BUX	Hungary	Europe	02.01.1991
21	^CAC	CAC40	France	Europe	08.01.1965
22	^DAX	DAX	Germany	Europe	28.09.1959
23	^FMIB	FTSE MIB	Italy	Europe	02.01.1998
24	^FTM	FTSE250	Great Britain	Europe	31.12.1985
25	^HEX	HEX	Finland	Europe	02.01.1995
26	^IBEX	IBEX35	Spain	Europe	05.01.1987
27	^ICEX	ICEX	Iceland	Europe	31.12.1992
28	^MDAX	MDAX	Germany	Europe	29.02.1996
29	^MOEX	MOEX	Russia	Europe	22.09.1997
30	^OMXC25	OMX COPENHAGEN 25	Denmark	Europe	19.12.2016
31	^OMXR	OMX RIGA	Latvia	Europe	03.01.2000
32	DJI	Dow_Jones_Industrial_US	USA	Europe	27.05.1896
33	DJC	Dow_Jones_Composite_US	USA	Europe	23.12.1980
34	BVP	Bovespa_Index_Brazil	Brazil	Europe	12.07.1989
35	WIG20	WIG20_PL	Poland	Europe	16.04.1991
36	WIG	WIG_PL	Poland	Europe	16.04.1991
37	UX	UX_Index_Ukraine	Ukraine	Europe	03.11.1997
38	SOFIX	SOFIX_Index_Bulgaria	Bulgaria	Europe	26.11.2001
39	SAX	SAX_Index_Slovakia	Slovakia	Asia	03.07.1995
40	OSEAX	OSE_Index_Norway	Norway	Europe	03.01.1983
41	SMI	SWISS_Market_Index	Switzerland	Europe	01.07.1988
42	RTS	RTS_Index_USD_Russia	Russia	Europe	01.09.1995
43	PSI20	PSI20_Index_Portugal	Portugal	NorthAmerica	31.12.1992
44	SDXP	sDAX_Germany	Germany	NorthAmerica	15.03.1999
45	PX	PX_Index_Czech	Czech Republic	SouthAmerica	07.09.1993
46	UKX	UK100CFD_United_Kingdom	Great Britain	Europe	13.11.1935
47	IPSA	IPSA_Index_Chile	Chile	Europe	02.01.1987
48	OMXT	OMX_Tallinn_Index_Eston	Estonia	Europe	03.01.2000
49	OMXV	OMX_Viilnius_Index	Lithuania	Europe	03.01.2000

50	MRV	Merval_Index_Argentina	Argentina	Europe	04.04.1988
51	XU	XU100_Turkey	Turkey	Europe	02.01.1990
52	NDX	Nasdaq_100_U.S.	USA	Europe	01.10.1985
53	DJT	Dow_Jones_Transportation_U.S.	USA	Europe	26.10.1896
54	CRY	CRB_Commodity_Index	Freight	Europe	03.01.1994
55	TSX	TSX_Composite_Canda	Canada	Europe	31.01.1956
56	TASI	tasi_Tadawul_All_Share_Index	Arabia Saudi	Europe	12.07.2001
57	DJU	Down_Jones_Utilities_U.S.	USA	Europe	02.01.1929
58	SPX	S&P 500 U.S.	USA	Europe	01.05.1789
59	IPC	Mexican_Boelsa_Index_Mexico	Mexico	SouthAmerica	08.11.1991
60	NDQ	Nasdaq_Composite_U.S.	USA	Europe	03.01.1938
61	TDXP	TexDAXGermany	Germany	Europe	16.09.1999
62	OMXS	OMXS_Stockholm_30_Index_Sweden	Sweden	Europe	30.09.1986
63	TOP40	JSE Top 40		SouthAmerica	03.07.1995

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FROM ENTREPRENEURIAL DISCOVERY PROCESSES TO DEPLOYMENT – GOVERNING CRITICAL TECHNOLOGIES IN INDUSTRIAL REGIONS

Mariusz KRUCZEK[1*], Paweł ZAWARTKA[2]

[1] Central Mining Institute – National Research Institute, Katowice; mkruczek@gig.eu, ORCID: 0000-0002-5052-3729
[2] Central Mining Institute – National Research Institute, Katowice; pzawartka@gig.eu, ORCID: 0000-0003-2038-2782
* Correspondence author

Purpose: This research investigates the influence of regional governance mechanisms on the deployment of critical technologies in industrial regions, specifically addressing the persistent gap between entrepreneurial discovery processes (EDP) and practical implementation at the firm and value chain levels. The study seeks to develop and empirically test a diagnostic framework that elucidates the transition from EDP to deployment within the context of smart specialisation, employing academic language and analytical rigour throughout.
Design/methodology/approach: The study adopts a mixed-methods exploratory and explanatory design, developing three semiquantitative diagnostic indices: the Governance Coordination Index (GCI), the Adoption Readiness Index (ARI), and the Value Chain Resilience Index (VCRI). The framework is empirically validated through an in-depth case study of the Silesian Voivodeship, integrating documentary analysis of RIS3 strategies and EDP reports (2019-2024), quantitative assessments from innovation dashboards, and 12 semi-structured stakeholder interviews. Each index is calibrated on a 0-2 scale across multiple dimensions, with methodological triangulation employed to enhance validity.
Findings: The Silesian Voivodeship demonstrates strong institutional coordination (GCI: 8/10) but shows notable weaknesses in adoption readiness (ARI: 5/8) and value chain resilience (VCRI: 5/8). The analysis uncovers a "governance-implementation asymmetry" where formal coordination mechanisms are well-developed, yet EDP processes remain limited, TRL-IRL convergence is weak, and resilience varies across sectors. Advanced manufacturing and medical technologies display stronger adaptive capacity compared to energy-related value chains.
Research limitations/implications: The study is limited by its single-case design and reliance on semi-quantitative expert judgment; however, data triangulation mitigates these concerns. Future research should undertake comparative studies across regions with varying industrial profiles and employ longitudinal designs to track adoption trajectories during external shocks. Incorporating quantitative firm-level indicators would complement the existing approach.
Practical implications: Regional authorities should focus on three key areas: increasing SME and end-user participation in EDP processes, creating targeted adoption tools that address the TRL-IRL gap (including managerial training and innovation-focused procurement), and fostering systemic resilience through coordinated supply chain platforms. These findings

guide policy development for regions experiencing industrial transformation within the EU's critical technologies agenda.
Social implications: The research supports just transition policies in industrial regions by identifying bottlenecks in technology deployment that impact employment, competitiveness, and sustainable development. It offers guidance for strengthening regional innovation ecosystems' capacity to tackle societal challenges through effective governance of critical technologies in areas such as clean energy, healthcare, and digital transformation.
Originality/value: This study introduces a diagnostic framework that operationalises the EDP-to-deployment pathway using three integrated indices. It advances theoretical understanding of governance-implementation dynamics in regional development, and provides practitioners with practical tools for assessing and improving technology adoption readiness in industrial regions transforming.
Keywords: smart specialisation, entrepreneurial discovery process, critical technologies, regional governance.
Category of the paper: Research paper.

1. Introduction

Discussions on critical technologies highlight not only the importance of setting priorities but also the capacity of regional innovation systems to support the transition from entrepreneurial discovery to effective adoption within firms and value chains. Governance, in this context, is understood as the arrangement of roles, coordination mechanisms, and policy instruments that connect administration, business, science, and users within a smart specialisation framework (Foray, 2014; Flanagan et al., 2011; McCann, Ortega-Argilés, 2015). In industrial regions such as the Silesian Voivodeship, critical technologies are expected to strengthen economic resilience while speeding up structural change, thus requiring coherent policy combinations and integrated risk management across infrastructures and supply chains (Řehák et al., 2022; Guijarro et al., 2024).

Building upon this foundation, a governance framework, here referred to as the pathway from Entrepreneurial Discovery Process (EDP) to deployment, has been proposed to connect entrepreneurial discovery with concrete implementation. This framework consists of three interconnected dimensions: firstly, the coordination of actors and participatory decision-making processes from priority setting to resource allocation within RIS3; secondly, transition instruments that convert strategic priorities into firm-level adoption, including technology roadmapping, technological due diligence, and targeted capability building within clusters and SMEs (Phaal et al., 2004; Zahra, George, 2002); thirdly, system learning achieved through ongoing monitoring and adaptive adjustment of the policy mix, where demand-side tools act as supportive enablers rather than main drivers (Bogers et al., 2018; Gottinger et al., 2025). Effectiveness in this context is assessed not only through programme inputs and outputs but

also by the maturity of implementation levels and the resilience of the value chain within sectors considered crucial for regional development (Frank et al., 2019; Yin, 2022).

Existing research on innovation management and Industry 4.0 emphasises that the adoption of digital technologies improves transparency and responsiveness when integrated within suitable managerial practices and absorptive capacity at both firm and ecosystem levels (Zahra, George, 2002; Bogers et al., 2018). At a regional level, varied digitalisation patterns among SMEs and the structural composition of clusters influence adoption routes, highlighting the need for governance and capability-building efforts tailored to local industrial contexts (Delgado et al., 2016; Chiappinelli et al., 2025). Using Silesia as a case study of a mature industrial economy undergoing simultaneous energy and digital transitions, this analysis explores how effectively the proposed governance architecture bridges the gap - the "last mile" - between entrepreneurial discovery and implementation within firms and along value chains (Foray, 2014; McCann, Ortega-Argilés, 2015).

2. Conceptual framework

The reviewed literature on smart specialisation, regional innovation systems, and critical technologies consistently highlights a persistent gap between setting strategic priorities and their practical implementation at the level of firms and clusters. While the Entrepreneurial Discovery Process (EDP) has gained widespread acceptance as a participatory mechanism for identifying innovation areas, many authors point out that later stages, such as supporting adoption, coordinating policies, and monitoring, often remain fragmented or poorly developed (Foray, 2014; Flanagan et al., 2011; McCann, Ortega-Argilés, 2015; Aranguren et al., 2018). This issue becomes especially evident in regions with strong industrial histories, where institutional complexity and overlapping mandates weaken the connection between discovery and execution. Recent European policy frameworks emphasise the need to close this gap. For example, the 2023 Commission Recommendation on Critical Technologies and the 2024 STEP regulation both stress the importance of strong regional governance mechanisms to promote technology development and adoption across ecosystems, particularly in sectors considered strategically important.

In addressing these challenges, this article proposes a conceptual framework based on three mutually reinforcing pillars designed to transform identified priorities into concrete implementations. The first pillar emphasises coordination and participation, regarded as a meta-capability that identifies who is involved in strategic decision-making, assigns responsibilities, and involves implementation actors early on. In advanced industrial regions, these coordination functions are often housed within cluster organisations and innovation ecosystems, thus connecting public policy instruments with firm-level needs (Delgado et al., 2016; Foray,

2014). When such structures are well developed, implementation barriers are managed proactively, and projects more reliably align with broader regional development goals. Indicators of coordination maturity include (Flanagan et al., 2011; McCann, Ortega-Argilés, 2015; Bzhalava et al., 2022):

- clearly formalized governance roles,
- transparent criteria aligning RIS3 objectives with project selection,
- regular EDP cycles involving implementation stakeholders,
- joint fora facilitating cross-level strategic steering.

Together, these factors reduce transaction costs and uncertainty, making it more likely that strategic areas will become actionable investments.

However, strategic coordination alone rarely suffices to ensure that regional priorities turn into concrete deployments. Many innovation systems face operational challenges in bridging the gap between intent and action, particularly when navigating fragmented value chains and diverse firms. As Zahra and George (2002) argue, a firm's absorptive capacity, particularly within small and medium-sized enterprises (SMEs), depends not only on technological potential but also on organisational readiness and effective intermediation. To address this operational gap, the second pillar highlights transition tools - mechanisms that link the strategic outputs of the EDP with firm-level adoption processes. Technology roadmapping is particularly noteworthy among these tools as a planning instrument that converts long-term innovation ambitions into sequenced, time-bound investments. Phaal et al. (2004) show that when roadmaps are co-created with various stakeholders, they act as effective coordination devices across public policy, firms, and research organisations, especially in contexts where emerging technologies lack established pathways to commercialisation. Another crucial tool is technological due diligence, a structured method for assessing a project's technological maturity, implementation risks, and systemic importance. Starzyńska's (2019) analysis of Polish industrial policy reveals how such assessments expose bottlenecks in regional innovation support instruments, particularly when adoption necessitates cross-sectoral integration.

Furthermore, direct support for adoption is vital. Frank et al. (2019) emphasise that digital transformation efforts in manufacturing tend to yield better results when paired with organisational change support, rather than relying solely on equipment funding. Likewise, Chiappinelli et al. (2025) emphasise the importance of advisory services that enable firms to align their regional priorities with internal investment strategies. Public-private pilot projects also help reduce adoption risks by allowing technical and organisational validation in real-world conditions. Embedded within cluster frameworks or value-chain consortia, these pilots promote knowledge exchange and policy learning (Bogers et al., 2018). Overall, these tools form an intermediate governance layer that converts strategy into practice by supporting iterative, context-sensitive transitions instead of enforcing top-down mandates.

The third pillar emphasises the necessity for regional governance systems to pursue systemic learning, characterised by continuous monitoring of implementation outcomes, early identification of potential failures, and the adaptive adjustment of policy tools. Instead of viewing monitoring as just a compliance task, recent scholarship advocates a formative evaluation approach that integrates policy learning within iterative feedback loops (Haddad et al., 2022). It has been stressed that governance should go beyond project-specific performance metrics to include systemic indicators like value chain resilience, absorptive capacity, and sectoral spillovers. These metrics offer a more complete assessment of whether innovation policies truly transform systemic conditions, rather than merely supporting incremental improvements (Yin, 2022). This distinction is especially vital in regions undergoing structural change, where institutional inertia can obscure weak adoption dynamics. Supporting this view, Řehák et al. (2022) observe that traditional performance indicators often fail to measure progress from goal setting to market-ready solutions. As a result, governance structures are encouraged to incorporate adaptive cycles, where programme designs develop responsively based on implementation feedback. This aligns with broader trends towards mission-oriented innovation policies, which promote experimentation and incremental adjustments (Mazzucato, 2018).

From a practical perspective, effective systemic learning requires robust data infrastructures and incentives that promote shared accountability among relevant parties. Regions that invest in multi-level monitoring platforms, integrating public authorities, clusters, and companies, are better equipped to adjust funding allocations, scale successful pilot initiatives, or stop underperforming programmes. Such platforms improve reflexivity, allowing for a critical reassessment of policy assumptions in light of new evidence. Within this framework, adaptability becomes a fundamental design principle rather than an additional characteristic. Regional systems that demonstrate dynamic learning capabilities - driven by real-time action rather than solely by retrospective evaluations - are more likely to convert EDP outputs into sustained technological adoption and secure a strong strategic position within emerging markets (European Commission, 2023; Guijarro et al., 2024).

All three pillars (figure 1) - coordination and participation, transition tools, and systemic learning - form a governance framework that implements the pathway from entrepreneurial discovery to firm-level deployment. Each pillar focuses on a different stage of this process: setting the agenda and aligning stakeholders, turning strategic priorities into investment-ready projects, and adaptive implementation guided by ongoing feedback. Notably, this process is iterative rather than strictly linear. For example, roadmaps may be adjusted based on monitoring insights, while coordination platforms can broaden or narrow their scope in response to adoption experiences.

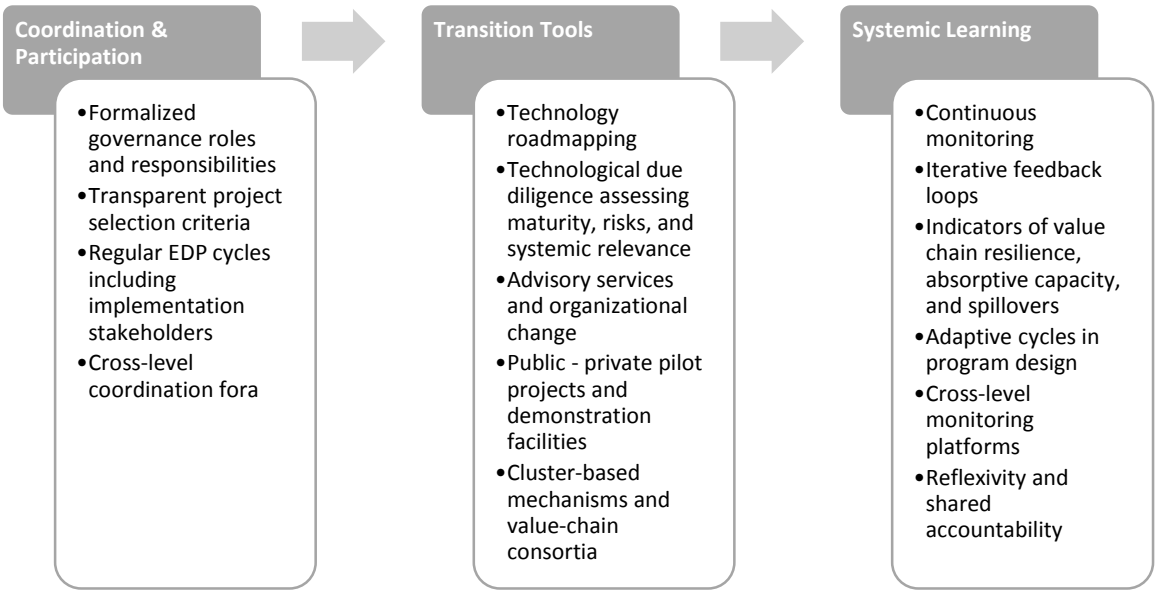


Figure 1. Conceptual Framework: Governance Architecture from Entrepreneurial Discovery Process to Technology Deployment.

Source: own study based on Foray, 2014; Flanagan et al., 2011; McCann, Ortega-Argilés, 2015; Aranguren et al., 2018.

Beyond serving as a normative model, this architecture also functions as an analytical tool to evaluate how prepared regional innovation systems are to deploy critical technologies effectively. By emphasising governance capabilities rather than specific technology or sector factors, it enables cross-regional comparisons among areas experiencing similar structural changes. It is essential to recognise that while conceptual models offer valuable frameworks for understanding innovation processes, the realities of implementing technology are often far more complex. Regional innovation systems are dynamic and diverse ecosystems where participants differ greatly in experience, resources, and motivations. This heterogeneity frequently leads to unforeseen challenges during deployment. Therefore, effective governance requires not only formal mechanisms but also flexibility and ongoing learning to adapt to local conditions and the specific needs of stakeholders.

Empirically, such a framework proves essential in contexts like the Silesian Voivodeship, where it can identify leverage points, uncover coordination gaps, and delineate barriers that obstruct implementation. It also enables the evaluation of alignment between RIS3 priorities, support instruments, and actual deployment outcomes within regional value chains. The following section applies this conceptual framework to a region undergoing industrial transition, illustrating how governance capabilities influence the real-world dynamics of critical technology adoption.

3. Methods and data

This study uses a mixed-methods approach, following an exploratory–explanatory sequence, to investigate how regional governance mechanisms affect the deployment of critical technologies in the Silesian Voivodeship. The methodological design is closely aligned with the conceptual model outlined earlier and centres on three diagnostic indices: the Governance Coordination Index (GCI), the Adoption Readiness Index (ARI), and the Value Chain Resilience Index (VCRI). These indices are designed not as universal measures, but as structured, context-sensitive tools that capture how institutional configurations turn innovation priorities into practical implementation (Creswell, 2014; Plano Clark, Ivankova, 2016).

These indices were developed drawing on recent research into innovation governance and systemic resilience. The Governance Coordination Index (GCI) expands on the work of McGregor et al. (2021), who stress the crucial role of coordination across various administrative levels in complex areas such as land use planning and risk management. Additionally, Geng and Huang (2022) have highlighted the importance of integrated coordination within multidimensional policy environments, proposing frameworks suitable for multi-faceted governance metrics. Markard and Truffer (2008) and Könnölä et al. (2021) offer further conceptual insight, examining the capacities for multi-level governance within innovation systems.

The Adoption Readiness Index (ARI) builds on research into institutional readiness and adoption capacity, drawing on insights from Ioannou and Serafeim (2019) on how governance legacies, socio-economic contexts, and organisational competencies jointly impact innovation diffusion (Cohen, Levinthal, 1990; Todorova, Durisin, 2007). The Value Chain Resilience Index (VCRI) incorporates recent findings on supply chain robustness and digitalisation, focusing particularly on the role of Industry 4.0 technologies in improving adaptability under turbulent conditions (Guijarro et al., 2024; Yin, 2022; Christopher, Peck, 2004; Ivanov, Dolgui, 2020).

Instead of replicating existing measurement models, each index has been customised to reflect the unique institutional and policy dynamics typical of the Silesian context. Their design adheres to a semi-quantitative evaluative framework commonly used in policy foresight and regional strategy appraisal, which combines structured expert judgement with administrative and project-level data (Teräs et al., 2020; Edler, Fagerberg, 2017). The structure and weighting of the indices were developed through a synthesis of theoretical foundations and empirical data gathered throughout the study. The credibility of this mixed-method approach is supported by expert elicitation and data triangulation methodologies, as recommended by Kelle et al. (2019) and Patton (2015).

The Governance Coordination Index assesses the extent to which institutional arrangements within the regional innovation system (RIS) are formal, participatory, and strategically aligned, from setting priorities to implementing policies. It assesses governance performance as the capacity to coordinate fragmented stakeholder input into effective action across government, academia, industry, and intermediaries. Five key dimensions underlie the GCI, drawing on previous studies of multi-level governance and innovation policy integration (McGregor et al., 2021; Geng, Huang, 2022):

1. Formalization of roles and responsibilities, assessed by the clarity and enforceability of governance documents such as RIS strategies and implementation roadmaps.
2. Frequency and inclusiveness of Entrepreneurial Discovery Process (EDP) cycles, operationalized via the number, composition, and documented feedback of participatory meetings (Foray et al., 2011; Grillitsch, Sotarauta, 2020).
3. Transparency in project selection criteria, measured by the accessibility and clarity of evaluation frameworks applied in allocating public resources.
4. Presence and quality of roadmaps, evaluated according to the existence of technology-specific or mission-oriented plans that incorporate milestones, key performance indicators, and responsible actors.
5. Institutionalized stakeholder coordination, determined by the establishment of multi-level coordination platforms, working groups, or innovation councils with formal mandates.

Each dimension was scored on a scale from 0 (absent or informal) to 2 (fully institutionalised and functional), based on a structured content analysis of RIS3 and EDP documents from 2019 to 2024, supplemented by 12 expert interviews with regional authorities, cluster coordinators, and innovation intermediaries. Experts were selected using purposive sampling to cover key components of the regional innovation system, ensuring representation of stakeholders directly engaged in RIS3 priority sectors and EDP processes. Scores were triangulated for validity and independently coded by two researchers. The GCI focuses on institutional coordination as a driver of implementation outcomes rather than an abstract measure of governance quality (Edquist, Hommen, 2008; Howlett, 2023).

The Adoption Readiness Index assesses the readiness of firms and intermediary institutions within the regional ecosystem to take on, implement, and spread crucial technologies. While the GCI focuses on governance architecture, ARI moves its attention to organisational and technical capabilities at the firm and cluster levels, mirroring the absorptive capacity concept (Zahra, George, 2002; Ioannou, Serafeim, 2019). ARI consists of four interconnected dimensions:

1. Convergence of Technology Readiness Levels (TRL) and Implementation Readiness Levels (IRL) within innovation projects (Mankins, 2009; ISO/IEC, 2012).
2. Firm-level implementation capabilities, gauged through involvement in adoption programs, evidence of pilot deployments, and internal investments in digital infrastructure.
3. Availability of cluster-based support mechanisms, such as dedicated innovation services, demonstration facilities, or specialised cluster initiatives targeting key technologies.
4. The technology deployment environment, including institutional facilitations like regional innovation hubs and market-facing mechanisms such as procurement pilots or testbeds.

Data sources included project documentation from regional development agencies, records from innovation intermediaries (e.g., technology parks, accelerators), and digital transformation metrics from public monitoring systems (e.g., SME digitalisation dashboards). Additional insights were gained from interviews with programme coordinators and project managers. Each ARI dimension was scored on a scale of 0 to 2, resulting in a maximum total score of 8. A representative sample of 45 innovation projects funded through the RIS3 strategy between 2020 and 2023 was analysed for TRL-IRL convergence. The index aims to identify systemic enablers and bottlenecks affecting the regional adoption trajectory rather than exhaustively measuring all innovation capacities.

The Value Chain Resilience Index measures the capacity of regional firms and industrial ecosystems to withstand, adapt to, and recover from technological, environmental, or market disruptions. This index complements the GCI and ARI by focusing on the operational resilience of interconnected business networks. Building on recent studies of industrial resilience during crises such as the COVID-19 pandemic and supply chain digitalisation (Guijarro et al., 2024; Yin, 2022; Hambali, Adhariani, 2024), the VCRI consists of four dimensions:

1. Supplier diversification, quantified by the number and geographic origin of active suppliers in critical RIS sectors (e.g., energy, materials, machinery).
2. Recovery time, measured as the estimated duration for restoring supply chain operations post-disruption, based on historical data and expert judgment.
3. Transparency and data sharing, reflected by the availability of digital platforms enabling end-to-end supply network visibility.
4. Crisis adaptation capabilities, encompassing redundancy mechanisms, reconfiguration potential, and documented experience managing disruptions.

Data were collected through structured interviews with business associations, cluster reports, supply chain mappings, and secondary sources, including digital transformation assessments of Polish SMEs. Special emphasis was placed on value chains identified as strategic in RIS3 and relevant national foresight documents. Each dimension was rated on a 0-2 scale, resulting in a maximum VCRI score of 8. Resilience is understood as an evolving

capacity shaped by exposure, responsiveness, and coordination, making the VCRI a proxy for "implementation maturity" in strategic sectors.

Together, the GCI, ARI, and VCRI enable a comprehensive, multidimensional assessment of the Silesian region's readiness to move from "EDP to deployment". The following section applies this diagnostic framework empirically, examining how institutional and economic structures support or hinder the adoption of critical technologies in practice.

4. Case Study: Silesian Voivodeship

Poland's Silesian Voivodeship is one of the country's most industrialised and historically rooted regions, with a development path closely tied to coal mining, metallurgy, and heavy industry. However, over the past 20 years, the region has faced dual pressures: the need for decarbonisation and industrial restructuring, and the imperative to adopt digital transformation in line with the European Industry 4.0 agenda. These pressures have made Silesia a key testing ground and focal point for national and EU-level strategies on just transition, technological upgrading, and innovation governance (Silesian Voivodeship, 2020, 2021, 2022; Resources for the Future, 2022). Within this context, the regional innovation system has evolved under the RIS3 framework, with Entrepreneurial Discovery Processes (EDP) promoted as key mechanisms for priority setting and stakeholder inclusion. Since 2014, the region has completed several EDP cycles, identifying strategic technological areas such as clean energy, medical technologies, the green economy, ICT, and advanced manufacturing, which align directly with European critical technology agendas in sustainability, renewable energy, digitalisation, and health resilience (Silesian Voivodeship, 2019).

Despite this ambitious approach, empirical evidence shows ongoing challenges in aligning institutional governance with firm-level adoption capacities. Interviews with regional stakeholders reveal significant coordination gaps between public authorities, cluster organisations, and companies, especially in turning formal strategies into practical support mechanisms. A common concern is the limited absorptive capacity of SMEs, which often lack sufficient managerial and financial resources to adopt advanced technologies in practice. This weakness is further exacerbated by the fragmented and sometimes overlapping nature of regional support instruments. The COVID-19 pandemic and the supply chain disruptions of 2022-2023 made these gaps more evident, exposing structural vulnerabilities in time-sensitive industries and emphasising the need for systemic adaptability in a region heavily dependent on industrial value chains.

Against this backdrop, the Silesian Voivodeship serves as a key example for applying the diagnostic framework developed in this study. The operationalisation of three indices - Governance Coordination, Adoption Readiness, and Value Chain Resilience - followed

a systematic approach that combined documentary evidence, statistical indicators, and qualitative insights. Strategic frameworks (RIS3 Strategies, the regional Technology Development Programme, and EDP reports) and project portfolios from 2019 to 2024 were systematically coded to identify the presence or absence of governance and adoption mechanisms. Complementary data from regional dashboards and Observatories provided measurable proxies, such as SME participation in innovation programmes or indicators of supplier diversification. Lastly, 12 semi-structured interviews were conducted with officials, cluster coordinators, entrepreneurs, and researchers to triangulate findings and validate ambiguous results, thereby enabling a more nuanced interpretation of both quantitative and documentary evidence.

Taken together (Table 1), the empirical results suggest that the Silesian Voivodeship combines institutional consolidation in governance with selective, cluster-based adoption capacity and asymmetric resilience across sectors. This configuration underscores the partial functional coupling of its innovation system, where well-developed institutional coordination mechanisms coexist with a weak capacity for systemic adoption and resilient transformation.

Table 1.
Diagnostic index results for the Silesian Voivodeship (2019-2024)

Index	Dimensions (0-2 scale)	Total score	Interpretation
Governance Coordination Index (GCI)	• Roles (2) • EDP inclusiveness (1) • Transparency (2) • Roadmaps (1) • Coordination (2)	8/10	Strong institutional frameworks, but inclusiveness and roadmap implementation remain weak
Adoption Readiness Index (ARI)	• TRL–IRL convergence (1) • Firm capabilities (1) • Cluster support (2) • Deployment environment (1)	5/8	Adoption concentrated in clusters, with systemic SME bottlenecks
Value Chain Resilience Index (VCRI)	• Supplier diversification (2) • Recovery time (1) • Transparency/data (1) • Crisis adaptation (1)	5/8	Uneven resilience: stronger in advanced manufacturing, weaker in energy-related chains

Source: own research.

With a score of 8/10, the Governance Coordination Index (GCI) highlighted both the institutional maturity of regional frameworks and ongoing systemic shortcomings. The score was boosted by the formalisation of mandates and responsibilities within bodies like the Regional Innovation Council, as well as the transparency of project selection criteria, which were widely seen as predictable and accessible. The coordination of stakeholders across regional, national, and EU levels was also assessed positively. However, inclusiveness remained an issue: while universities and cluster organisations regularly participated in EDP consultations, SME contributions were often marginal and viewed by entrepreneurs as symbolic. A similar structural weakness was found in relation to roadmapping exercises, which although present for sectors such as clean energy and health technologies, rarely led to concrete

operational milestones or budgetary commitments. These disparities reflect a governance-implementation imbalance (McCann, Ortega-Argilés, 2015): while procedural transparency and formalisation are well advanced, mechanisms ensuring substantive inclusiveness and practical follow-through remain weak.

According to the Adoption Readiness Index (ARI), which scored 5/8, Silesia has a significant adoption capacity in certain areas, but it hasn't yet been widely disseminated across the economy. Projects funded by RIS3 show that while technologies often reached mid-to-high Technology Readiness Levels (TRL 6-7), they didn't align with Implementation Readiness Levels as much. This gap between technology and organisational readiness reflects the limited financial and managerial skills of companies, as well as the limited spread of support mechanisms beyond leading clusters. A lack of investment in digital infrastructure and workforce training particularly limited small and medium-sized enterprises (SMEs) in metallurgy and traditional manufacturing. However, successful cluster-led initiatives, such as the Medical Technology Accelerator in Zabrze or pilot infrastructures in Gliwice, including labs at the Silesian University of Technology and innovation spaces supported by GAPR, demonstrate the potential for targeted interventions to lead to tangible improvements. Nevertheless, a structural limitation remains in the deployment environment: insufficient procurement pilots and underdeveloped testbed facilities hinder the translation of promising prototypes into market-ready solutions.

The Value Chain Resilience Index (VCRI) also scored 5/8, indicating that resilience remains unevenly distributed across sectors. While advanced manufacturing and medical technologies showed relatively strong supplier diversification and cross-border integration with Central European networks, energy-related value chains appeared more vulnerable, especially in recovery time after supply disruptions. The 2022 automotive shortages, which caused multi-month delays, highlighted these weaknesses. Transparency and information-sharing mechanisms were limited: large firms have mainly implemented ERP and SCM platforms, whereas SMEs continue to depend on informal communication, preventing systemic visibility. Efforts to integrate adaptive mechanisms, such as pilots in circular economy practices, remain highly fragmented and lack the necessary cross-sectoral coordination for scaling.

The case thus illustrates a broader pattern observed in industrial regions undergoing structural transition: while institutional maturity and transparent frameworks are established, the “last mile” of implementation, reflected in inclusiveness, firm-level capabilities, and resilience, remains insufficiently secured (Edler, Fagerberg, 2017; Foray et al., 2011). For policy and practice, this implies three critical needs: deepening the inclusiveness of EDP processes, particularly through SME and end-user engagement; enhancing adoption capacity through targeted managerial and financial instruments that bridge the TRL-IRL gap; and embedding resilience via integrative tools such as digital supply chain platforms and coordinated adaptation strategies. Addressing these bottlenecks is essential if the Silesian Voivodeship is to progress from an administratively consolidated innovation system to

a functionally resilient region capable of translating strategic priorities into sustained technological deployment in line with the EU's agenda for critical technologies and open strategic autonomy.

5. Discussion and Conclusions

The influence of regional governance mechanisms on the deployment of critical technologies was examined, with a particular focus on the Silesian Voivodeship as a case study. A mixed-methods approach was used, operationalising three diagnostic indices: the Governance Coordination Index (GCI), the Adoption Readiness Index (ARI), and the Value Chain Resilience Index (VCRI). These indices collectively provide a robust framework for assessing how institutional coordination, organisational readiness, and systemic resilience interact to determine the extent to which Entrepreneurial Discovery Processes (EDP) lead to concrete technological deployments within firms and across value chains.

The findings demonstrate that substantial progress has been achieved in establishing governance frameworks, enhancing transparency in resource distribution, and developing coordination platforms within the region. However, challenges remain. The inclusiveness of EDP cycles is still limited, a clear gap between technology readiness levels (TRL) and implementation readiness levels (IRL) is apparent in many projects, and resilience differs greatly across sectors. Notably, the real-world impacts of these governance arrangements intersect with broader phenomena seen in other industrial and post-industrial economies, where the deployment of advanced (particularly digital and AI-based) technologies introduces both new opportunities and complex societal challenges.

Recent international analyses highlight that the acceleration of generative artificial intelligence and automation is transforming skill requirements and reshaping regional employment landscapes far beyond traditional industrial settings. The OECD (2024) reports that generative AI increasingly distinguishes between urban and rural labour markets, potentially exacerbating digital divides and existing spatial inequalities – a trend also visible in Silesia, where reskilling needs are most acute among workers in declining industries and less connected localities. At the same time, the World Economic Forum (2025) identifies that nearly 60% of workers globally will need some form of upskilling by 2030, and that regions with accessible, well-coordinated retraining programmes are best positioned to navigate these transitions. Silesia's regional policy focus on reskilling, digital infrastructure, and support for SMEs thus aligns with emerging best practices but must continuously adapt to the shifting nature of technological change (OECD, 2024; World Economic Forum, 2025).

Three main theoretical contributions are identified. Firstly, the study demonstrates how semi-quantitative diagnostic indices can convert abstract governance concepts into measurable and comparable formats across various regional contexts — integrating multi-level governance literature (Markard, Truffer, 2008; Könnölä et al., 2021) with empirical coding. Secondly, the analysis broadens the discussion on absorptive capacity (Cohen, Levinthal, 1990; Zahra, George, 2002), suggesting that institutional consolidation primarily benefits larger, networked firms, while SMEs and peripheral communities often face cumulative disadvantages in reskilling and adaptation. Thirdly, sectoral fragmentation in resilience is evident: highly internationalised clusters display strong adaptive capacities, whereas energy-intensive and less diversified sectors remain more vulnerable, confirming trends emphasised by recent comparative studies (Yin, 2022; Ivanov, Dolgui, 2020).

This discussion also has practical implications. Regional policymakers should remember, based on both local evidence and international experience, that governance needs to go beyond merely following procedures. It should actively promote inclusiveness, flexibility, and cross-sector collaboration. This involves providing targeted support to SMEs, improving access to reskilling and training- especially outside cluster hubs- and establishing feedback systems to detect and address new inequalities. Implementing pilot facilities, demo testbeds, and cluster services is crucial for closing TRL-IRL gaps and achieving fairer labour market results. Lastly, building resilience, especially for vulnerable groups and peripheral regions, requires ongoing investment in digital and social infrastructure and forming partnerships that guarantee no worker or area is left behind during the technological transition (OECD, 2024; World Economic Forum, 2025).

The study's limitations are acknowledged, especially its focus on a single case with an industrial legacy and institutional context that may not apply to other areas, such as urban knowledge economies. The semi-quantitative indices and reliance on expert judgment introduce some subjectivity, though this is reduced through data triangulation. Additionally, the timeframe (2019-2024) restricts the ability to evaluate long-term policy effects. These constraints suggest avenues for future research, including comparative analyses to see if governance-implementation gaps are common across industrial transition regions or unique to Central and Eastern Europe. Long-term studies could also explore how adoption readiness and resilience evolve over time amid repeated shocks like energy crises or digital disruptions. Adding firm-level quantitative data on innovation could strengthen the semi-qualitative indices, allowing for more accurate benchmarking across different regions.

Overall, the Silesian case demonstrates both the potential and the limitations of regional innovation systems. While institutional maturity and transparency are essential foundations, they alone are not sufficient to guarantee successful deployment. To connect entrepreneurial discovery with implementation, governance must be inclusive, support systemic adoption, and enhance resilience across value chains. Placing these findings within the broader European discussion on critical technologies and strategic autonomy (European Commission, 2023), this study offers a framework that is both analytically sound and practically useful.

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Appendix

Coding Framework with Illustrative Quotes

Main Category	Subcategory / Code	Description	Illustrative Quote
Governance Coordination	Formalization of roles	Clarity of responsibilities in RIS3 and EDP governance	"Responsibilities are well described in the RIS3 strategy, but in practice overlaps still occur between regional agencies" (Regional authority)
	EDP inclusiveness	Degree of SME and end-user participation	"Most meetings involve universities and clusters – SMEs are usually informed, not actively engaged" (Cluster coordinator)
	Transparency	Visibility of project selection criteria	"We know in advance what evaluation criteria will be applied, which makes the process predictable" (Entrepreneur)
	Roadmapping	Existence and operationalization of technology roadmaps	"Energy sector roadmaps exist, but they lack milestones connected to funding" (Researcher)
	Coordination platforms	Multi-level collaboration mechanisms	"The Innovation Council works well as a forum, but decisions often remain at the discussion stage" (Regional policymaker)
Adoption Readiness	TRL-IRL convergence	Gap between technological maturity and implementation capacity	"Projects often reach TRL 6 or 7, but companies don't have resources to commercialize them" (SME manager)
	Firm-level capabilities	Organizational and financial readiness	"We lack skilled staff to operate new digital systems, even if the technology is available. (Entrepreneur)
	Cluster support	Availability of specialized services	"The medical technology accelerator in Zabrze really helps with pilots and mentoring" (Cluster coordinator)
	Deployment environment	Procurement pilots, testbeds, innovation hubs	"There are too few testbeds to validate prototypes under real conditions" (Program manager)
Value Chain Resilience	Supplier diversification	Extent of alternative sourcing	"Larger firms diversify suppliers abroad, SMEs usually rely on one domestic provider" (Business association)
	Recovery time	Ability to restore operations after disruptions	"The automotive shortage showed it takes months to stabilize production chains" (Entrepreneur)
	Transparency and data	Use of digital platforms for supply chain visibility	"Big players use ERP systems, but smaller suppliers still communicate via phone and email" (Cluster coordinator)
	Crisis adaptation	Redundancy and reconfiguration capacities	"We experimented with circular economy pilots, but without systemic support they remain isolated" (Innovation intermediary)

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THE IMPORTANCE OF PERSON-ENVIRONMENT FIT IN SHAPING JOB SATISFACTION WITH MILITARY SERVICE

Dorota KUREK

War Studies University, Management and Command Faculty, Institute of Management;
d.kurek@akademia.mil.pl, ORCID: 0000-0002-2346-6108

Purpose: The concept of person-environment (PE) fit is grounded in interactional psychology, which posits that the interplay between individual characteristics and environmental attributes is a key determinant of human behavior, including job satisfaction. Understanding the conditions that shape satisfaction requires a comprehensive analysis of fit dimensions, as each may hold different significance from the individual's perspective. The aim of the study was to identify the relationship between person-environment fit and satisfaction with military service. The analysis focused on three dimensions of fit: person-group, person-supervisor, and person-organization, to determine which dimension most strongly influences soldiers' satisfaction.
Design/methodology/approach: The study was conducted at the end of 2023 using a diagnostic survey method. The sample consisted of 250 officers of the Polish Armed Forces, who completed a structured questionnaire.
Findings: The results provided empirical evidence of a statistically significant, positive relationship between person-environment fit and satisfaction with military service across all three dimensions. The strongest correlation was observed between person-organization fit and service satisfaction, underscoring the importance of this dimension.
Research limitations/implications: Due to the non-representative nature of the research sample, the results have limited generalizability.
Social implications: The findings confirm the need to analyze individual dimensions of fit to gain a deeper understanding of the factors influencing satisfaction with military service. This knowledge supports efforts to enhance soldiers' well-being and contributes to building the image of the military as an attractive employer.
Originality/value: The originality of this research lies in its application of the person-environment fit theory to the military context, which remains underexplored in organizational and psychological studies. By examining three distinct dimensions of fit: person-group, person-supervisor, and person-organization - the study offers a nuanced understanding of how different relational dynamics influence job satisfaction among soldiers. The empirical evidence highlights the dominant role of person-organization fit in shaping satisfaction, suggesting that alignment with institutional values and structures is particularly critical in hierarchical environments like the military. This approach extends the theoretical framework of PE fit beyond civilian workplaces, providing new insights into personnel well-being and retention strategies within armed forces.
Keywords: person-environment fit, job satisfaction, military service.
Category of the paper: Research article.

1. Introduction

The issue of person-environment fit has long been a subject of detailed interest among researchers, with the earliest publications on the topic dating back to the 1940s. A pivotal moment in the development of this research area occurred in the 1950s with Heron's studies, which linked vocational suitability with job satisfaction (Borucki, 1977), prompting deeper reflection on the complexity of the phenomenon. In the context of the person–organization relationship, the term "fit" was notably employed in the work of Muchinsky and Monahan (1987). Since then, the concept has been increasingly explored in academic journals and monographs, with a growing number of studies adopting a multidimensional approach to fit.

A comprehensive insight into the complexity of these analyses is provided by Subramanian, Billsberry, and Berett, who conducted a bibliometric review of publications from 1982 to 2020, identifying 887 scholarly articles focused on person-organization fit (PO). Through keyword analysis, the authors revealed that job satisfaction is among the most frequently associated variables with the concept of fit (2023). This article was inspired by the aforementioned study and aims to explore the relationship between person-environment fit and satisfaction with military service. The motivation for this inquiry stems from an identified research gap: although the link between fit and satisfaction has been examined across various professions and organizational levels, there is a noticeable lack of studies addressing this relationship within the context of military service.

The primary objective of the research was to identify the relationship between person-environment fit and satisfaction with military service. Both variables were operationalized with precise indicators, clarifying the conceptual framework and outlining the study's limitations. The analysis was made possible through empirical research conducted using a diagnostic survey method. The survey, carried out at the end of 2023, included a sample of 250 Polish soldiers.

The originality of the present study lies in the application of the person-environment fit concept within the context of military service, which has thus far remained outside the mainstream of scholarly analysis. This research addresses a significant gap by extending existing approaches to fit into a highly specific organizational setting - namely, the armed forces. The use of precisely operationalized indicators for both variables, combined with empirical data collected from a sample of 250 Polish soldiers, constitutes a valuable contribution to the development of knowledge in the field of human resource management in hierarchical organizations. The findings may enhance understanding of the factors influencing job satisfaction in high-risk and strictly disciplined organizational structures. An added value of the conducted research was the development of an original scale measuring person–environment fit, along with its subsequent validation. The developed original scale for assessing person–environment fit, validated within the scope of this study, may also be effectively applied in research conducted across other uniformed services.

2. Literature review

Recognizing work as a central activity in adult life, both theorists and practitioners in management, psychology, and sociology of work have devoted considerable attention to the issue of person-environment fit. Numerous studies focus on both individual and organizational aspects of fit. As Andysz emphasizes, the essence of fit lies in striving for an optimal allocation of resources that yields the greatest return in terms of satisfaction and material benefits (2011, p. 117). Physical, intellectual, and emotional resources possessed and utilized by employees are also subject to analysis, particularly in relation to their professional experiences.

A key assumption underlying the concept of fit is that it reflects the alignment between an employee's expectations and the characteristics of their job, thus constituting a form of relationship between the individual and the environment (Skłodowski, 2002). This opens the possibility of defining person-environment fit as a phenomenon occurring across multiple dimensions comparable to a synthetic indicator. The existence of these dimensions highlights the complexity of the concept and the need for research that goes beyond general fit to explore its scope and intensity within specific dimensions.

The concept of fit is addressed by a wide range of scholars and is also referred to as adaptation, congruence, or vocational fit. It can also be approached from a different perspective, emphasizing the role of organizational identity and the phenomenon of depersonalization. Czarnota-Bojarska notes that organizations function as social groups in which identity is shaped through categorization (2012). The construct of the "ingroup" (Turner, 1987) emerges when the self ("I") is replaced by the collective ("we"), leading to the substitution of individual goals and values with those of the group. This process results in empathic altruism (adopting group goals as one's own) and empathic trust (believing one's goals are shared by the group). Trust in others, stemming from perceived similarity and mutual alignment, enhances well-being and satisfaction within the environment and improves group effectiveness (Williams, 2001).

Hogg and Turner (1985) emphasize the reciprocal relationship between person-organization fit and identity: as fit increases, so does identification, which in turn strengthens fit and boosts motivation and performance. Depersonalization can also be observed through the ASA model (Attraction-Selection-Attrition), which suggests that organizational processes lead to homogenization - individual differences among employees diminish over time (Schneider, 1987). However, Schneider warns that this may hinder organizational development in the face of changing external conditions and emerging challenges.

Highlighting the complexity and specificity of fit, Czarnota-Bojarska distinguishes two situations in which the term applies: first, when different elements complement each other to form a coherent whole, and second, when elements belong to the same category (2010). Muchinsky and Monahan (1987) previously emphasized this duality in the context of person-organization fit, distinguishing between complementary fit (filling gaps) and supplementary fit

(similarity in goals and values). Thus, person-environment fit may refer to both complementarity and similarity between the individual and the environment, with a third dimension involving the degree of organizational identification.

Edwards (1991) further differentiated types of fit, highlighting "needs-supplies" fit where organizational resources meet employee expectations - and "demands-abilities" fit where employees meet organizational requirements (Czarnota-Bojarska, 2010). Kristof (1996) integrated these perspectives, defining supplementary fit as the similarity between organizational culture and personality, and complementary fit as the alignment between employee expectations and organizational resources, encompassing both needs-supplies and demands-abilities relationships.

The value of research on fit is reinforced by Czarnota-Bojarska's findings that supplementary fit is more strongly associated with employee productivity than complementary fit, underscoring the importance of fostering a sense of "we" and organizational identity (2012).

In examining person-environment fit, the literature identifies various dimensions, including:

- Person-organization fit (PO) – alignment of values and goals.
- Person-job fit (PJ) – correlation between job duties and individual skills, abilities, and needs.
- Person-organizational culture fit (POC) – acceptance and support of organizational culture.
- Person-vocation fit (PV) – relevance of vocational alignment, including competency gaps.
- Person-supervisor fit (PS) – compatibility with direct supervisors.
- Person-group fit (PG) – alignment with workgroup dynamics.

Each dimension can be assessed through two types of fit: objective and subjective. Objective fit is evaluated by third parties using external criteria (e.g., health status in military recruitment), while subjective fit involves personal perceptions and feelings - such as the belief of being in the right place - which are shaped by individual experiences (Andysz, 2012). In the context of long-term workplace functioning and talent retention, subjective fit is considered more influential.

Researchers investigating person-environment fit within organizational contexts examine both objective and subjective indicators. According to Kristof-Brown and Stevens (2001), subjective measures of fit exhibit stronger associations with workplace functioning. These measures not only influence employee behaviors and attitudes but, as Edwards and Cable (2009) emphasize, also contribute to enhanced well-being in the work environment. In light of this, the present study focused on subjective indicators of fit.

While the positive outcomes of fit - such as career stability, organizational loyalty, a supportive work atmosphere, a sense of competence, and comfort - are well-documented (Spokane et al., 2000; Chatman, 1989), it is equally important to consider the consequences of

misfit and overfit. Misfit may lead to increased absenteeism, reduced engagement and performance, while excessive fit, though less frequently discussed, can also have negative long-term effects. For instance, Vleugels and Flatau-Harrison (2023) note that excessive person-environment fit may result in decreased productivity, hinder personal growth and adaptability, and suppress creativity, leading to stagnation and complacency. Optimal fit, therefore, is not synonymous with perfect alignment; rather, a slight degree of misfit may generate positive stress and motivation for development (Edwards, 2008).

Studying person-environment fit requires particular attention, as fit is not a static value. It evolves under the influence of various factors, each of which may be differently evaluated by individuals. Fit is often assessed after actual changes, such as job adaptation or role transitions referred to as "actual fit". However, it is equally important to consider the psychological dimension of fit, which reflects an individual's perception of change over time, comparing past and present experiences and projecting future expectations. This can be termed "perceived fit". Jansen and Shipp (2011) describe this as a "fit narrative", which shapes the understanding of the variable.

Consequently, longitudinal studies of fit are recommended (Vleugels et al., 2023), rather than one-time assessments typically conducted after specific events (e.g., selection or adaptation). As Vleugels (2023, p. 11) points out, existing literature on temporal fit has focused on traditional (i.e., linear) forms of change, neglecting more complex (e.g., nonlinear) dynamics. It has favored forward causality (fit as a predictor) over reverse causality (fit as an outcome) and overlooked the temporal interplay between fit and misfit. This highlights the need for further research to explore the temporal properties of fit - its fluctuations and implications for individuals and organizations.

In conclusion, person-environment fit is a critical issue not only from an organizational perspective but also for individual employees. Emphasizing both organizational and personal consequences of fit enhances understanding of the importance of maintaining appropriate levels of fit and implementing strategies for its assessment. On an individual level, improved fit contributes to greater well-being, increased self-esteem, and enhanced interpersonal trust, while also fostering a more predictable environment that helps reduce stress.

Person-environment fit encompasses the full spectrum of human experiences related to the process of need fulfillment in the workplace. It is therefore inherently linked to the concept of managing employees' professional experiences, as confirmed by research conducted by Soni, Chawla, and Sengar (2017). Within the domain of person-environment fit, one of the key attitudes subject to investigation is job satisfaction, as it serves as a predictor of the durability of the employee-workplace relationship (Andysz, 2011). Measuring job satisfaction thus becomes a source of insight into subjective fit, with the scope of research depending on how satisfaction is defined and whether it is treated as a dependent or independent variable.

Job satisfaction refers to "a pleasurable or positive emotional state resulting from the appraisal of one's job or job experiences" (Locke, 1976, p. 1300). It is considered a multidimensional construct that integrates various factors (Newstrom, 2015), particularly those directly related to the nature of the work itself and the broader work context (e.g., work environment, colleagues). Nair defines job satisfaction as an attitude based on personal evaluation of one's professional position. In his view, satisfaction goes beyond emotions and includes how an employee perceives and assesses the value of their work. Thus, job satisfaction can be understood as a complex process in which individual experiences, expectations, and evaluations shape how one perceives their place within the organization. Nair emphasizes that this evaluation is a key factor influencing overall job satisfaction and motivation (2007).

In the context of vocational fit, Lipińska-Grobelny and Głowacka (2009) highlight the importance of the person-environment fit model as a determinant of job satisfaction. They argue that satisfaction may be related to the nature of tasks performed, employee characteristics, fit between the employee and the job, or a combination of these factors (Brief, 1998; Spector, 1997; Zalewska, 2003). Furnham and Walsh (1989; Furnham, 1991) found that vocational fit is associated with absenteeism and experienced stress - an issue particularly relevant in military service due to its stress-inducing nature and the need for personnel stability. It is important to note the link between fit and career stability. Robbins et al. (2017) associate job satisfaction with rewards, relationships with colleagues, and working conditions.

Since job satisfaction can be approached holistically as a dependent variable or analyzed through its specific dimensions - such as compensation and benefits, relationships with coworkers, and relationships with supervisors - it is reasonable to suggest that these dimensions partially correspond to the dimensions of fit. Referring to one of the most widely used tools for measuring job satisfaction - the Job Descriptive Index (JDI) developed by Smith, Kendall, and Hulin (1969) - it is worth noting that the JDI includes five key dimensions: the nature of the work itself, relationships with coworkers, relationships with supervisors, pay, and opportunities for promotion.

The relationship between satisfaction and fit - particularly person-organization fit - has been confirmed by studies conducted by Sheeraz Shah and Mehlab Ayub (2021) and Ambrose et al. (2007). The link between person-supervisor fit and job satisfaction was analyzed by Zheng, Jin, and Hahm (2008), while Klaic, Burtscher, and Jonas examined the impact of transformational leadership style within the person-supervisor fit dimension (2018). Deschênes (2021) explored person-environment fit across the dimensions of person-job, person-group, and person-supervisor in relation to job satisfaction. Her findings revealed that the importance of fit dimensions varies across generations. For example, person-group fit was found to be a key factor in building job satisfaction only among Generation Y, offering a valuable perspective for research in multigenerational work environments.

It can therefore be argued that the quality of fit in the dimensions of person-team, person-supervisor, and person-organization can be assessed by examining satisfaction within these respective areas.

Job satisfaction among soldiers is a matter of particular importance, not only at the individual level but, more significantly, at the societal level. Ensuring positive experiences in military service forms the foundation for building long-term and healthy relationships, which in turn contribute to increased retention rates and reduced turnover - key factors in maintaining personnel stability within the armed forces (Kurek, 2024). The issue of satisfaction in military service has been the subject of analysis by researchers worldwide, including Polish scholars (see Table 1).

Table 1.
Research Findings on Soldiers' Satisfaction with Military Service

Year	Author/s	Examined Variables and Conclusions
Research on Foreign Armed Forces		
1999	Nystedt et al.	The study included soldiers from the Swedish Armed Forces. The analysis focused on organizational commitment, work engagement, and job satisfaction. Particular attention was given to variables such as supervisor support and coworker support. A relationship between supervisor support and job satisfaction was confirmed; however, no empirical evidence was found to support a link between coworker support and job satisfaction.
2004	Sanchez et al.	A study on job satisfaction in the United States. The authors analyzed demographic, psychological, and physical factors. They found that job satisfaction decreases with the perception of relatively high levels of work pressure and poor relationships with supervisors.
2008	Yang et al.	The study examined the impact of salary increases on service satisfaction among junior officers in the Chinese army.
2012	Topa, Moriano	In studying the job satisfaction of Spanish soldiers, the authors focused on the relationships between organizational socialization tactics, job satisfaction, and turnover intention.
2015	Lopes et al.	The study included Portuguese sergeants and officers. The Job Descriptive Index (JDI) and Job in General (JIG) tools were used in the research. The findings revealed that salary and promotion opportunities emerged as the dimensions of job satisfaction most strongly associated with demographic variables.
2017	Alvinius et al.	A study on job satisfaction in the Swedish Armed Forces. An integrative theoretical model of job satisfaction and organizational commitment among senior officers was proposed.
2018	Makhathini, Van Dyk	A study on job satisfaction among members of the South African National Defence Force. The authors revealed a significant relationship between organizational climate, job satisfaction, and organizational commitment. They also emphasized the existence of a positive correlation between laissez-faire, transformational, and transactional leadership styles and organizational commitment.
2019	Fors Brandebo et al.	The study focused on constructive and destructive leadership behaviors as predictors of soldiers' experienced sense of meaningfulness at work and overall job satisfaction.
2024	Gargallo-Castel, Marzo-Navarro	In studying job satisfaction among Spanish soldiers, three key determinants of satisfaction were identified: the nature of the work itself, interpersonal relationships, and economic aspects.
2024	Dagher et al.	The study involved soldiers from the Lebanese Armed Forces. The research confirmed, among other things, the role of mental support provided by supervisors and attention to soldiers' well-being in shaping service satisfaction. Other factors influencing motivation and job satisfaction were also analyzed.

Cont. table 1.

Research within the Polish Armed Forces		
2013	Molesztak	The study involved enlisted soldiers. The analysis focused on how environmental support and psychological gender differentiate job satisfaction.
2015	Piotrowski, Kubacka	The study analyzed the relationship between satisfaction with life, marriage, and military service, and the intensity of work-family conflicts among personnel of the Polish Armed Forces.
2016	Majewski, Kurek	The analysis focused on factors of job satisfaction related to interpersonal relationships, the nature of the work performed, the work environment, and professional achievements.
2023	Bsoul-Kopowska	The study was conducted among officers from various uniformed services, focusing on factors contributing to job satisfaction. In the military context, it was revealed that over ninety percent of surveyed soldiers emphasized the importance of interpersonal relationships at work as a key factor in job satisfaction.

Source: Author's own work.

Considering the aforementioned research findings, it is worth noting that satisfaction with military service is often assessed through the measurement of interpersonal relationship quality - both in terms of relationships with supervisors and with peers - as well as through the analysis of the work itself, particularly in relation to person-organization fit. The quality of the relationship with one's supervisor is associated with mutual understanding, respect, and trust. Leadership style is also frequently examined as a determinant of satisfaction (Alzubi et al., 2023), a relationship confirmed by Aprillina et al. (2024) and, in the military context, by Makhathini and Van Dyk (2018). Valuable insights into the impact of constructive and destructive leadership styles on the satisfaction of Swedish soldiers were provided by Fors Brandebo et al. (2019), reinforcing the importance of analyzing supervisor relationships as a key factor influencing satisfaction.

While the relevance of peer relationships has also been explored, findings in this area remain inconsistent - statistically significant correlations are not always confirmed. The third area of interest concerns the organization itself. Research in this domain typically focuses on factors such as compensation and development opportunities, while less attention is paid to the individual's subjective sense of "fit" with the organization or the alignment between one's aspirations and the nature of the work - an aspect that may also be linked to the idea of service.

In conclusion, when examining person-environment fit among soldiers and its relationship with job satisfaction, it is appropriate to focus on three key dimensions: person-supervisor, person-group, and person-organization. In the context of satisfaction and overall professional experience, the degree of fit - measured through both vocational adequacy and mental alignment (i.e., the subjective sense of belonging within the organization) may correlate with job satisfaction and, consequently, with the quality of professional life. The strength of these relationships may reveal which areas of professional activity and thus which dimensions of fit play a significant role in shaping satisfaction with military service. These factors were therefore given particular attention in the present study.

3. Methods

The primary objective of the study was to provide empirical evidence of a statistically significant relationship between person-environment fit and satisfaction with military service. Accordingly, the main research question was formulated as follows: What is the relationship between person-environment fit and soldiers' satisfaction with military service? The hypothesis was stated as: There is a positive relationship between person-environment fit and satisfaction with military service.

Given that PE fit encompasses multiple dimensions, the study focused on selected dimensions: person-group fit, person-supervisor fit, and person-organization fit. While limiting the scope to three dimensions may be considered a methodological constraint, the author believes that the findings presented may serve as a foundation for further reflection on the need for a comprehensive analysis of all dimensions - particularly considering the specific nature of military tasks and the significance of service in the context of collective security.

The examination of these three dimensions required the operationalization of variables. A total of ten statements were analyzed, each corresponding to one of the selected dimensions. While person-group and person-supervisor fit have been extensively explored in the literature, the author identified a need to clarify the conceptualization of person-organization fit, which guided the direction of the study.

In this dimension, the analysis focused on alignment with the organization in terms of pride in service, service as the fulfillment of professional aspirations, service as a means of developing personal passions, and the belief that the soldier "fits" within the military. This approach examined fit at the level of values and identity - specifically, the congruence between an individual's values, beliefs, and identity, and the organization's culture, mission, and values. In the military context, this type of fit is particularly significant, as military service is often associated with a strong sense of mission and professional identity.

Pride in service is linked to the perception of military duty as an honorable and socially important role, as well as a sense of belonging to an elite group that protects the nation and its citizens. The fulfillment of aspirations and development of passions represents a critical area of fit, as it reflects the alignment between personal expectations and the opportunity for their realization. The belief that a soldier fits within the military refers to the perception of being well-suited to the military's culture and values, encompassing acceptance and identification with military norms, ethics, and lifestyle - factors that contribute to building a positive image of the armed forces.

Various tools are used to study person-environment fit, including the Minnesota Satisfaction Questionnaire (MSQ) for measuring job satisfaction, the Minnesota Satisfactoriness Scales (MSS) for assessing the degree to which occupational requirements are met, and the Minnesota Importance Questionnaire (MIQ) for evaluating the hierarchy of vocational needs. However,

none of these instruments allowed for the measurement of the dimensions of fit, which implied the need to develop a proprietary scale.

Following the operationalization of variables, the indicators were presented in Figure 1. In analyzing job satisfaction, the study focused on general satisfaction rather than its specific dimensions.

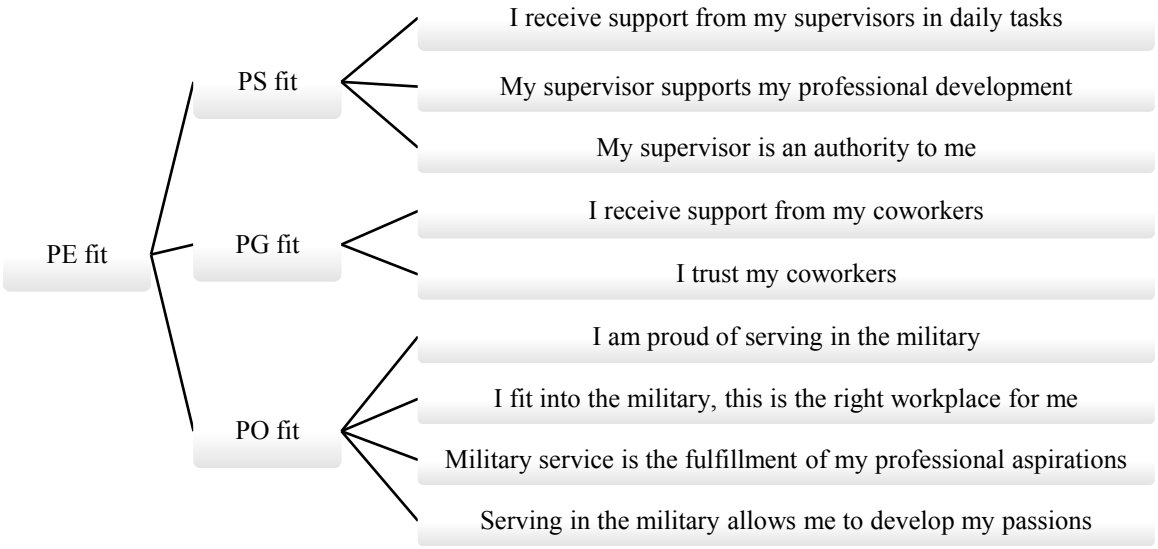


Figure 1. Scope of the research.

Source: Author's own work.

A five-point Likert scale was employed to examine the variables under study. In measuring person-environment fit across its distinct dimensions, the theoretical construct was first developed and the variables were operationalized.

To ensure the reliability of the measurement, Cronbach's alpha coefficients were calculated, assessing the internal consistency of items within each subscale corresponding to specific dimensions of fit. The internal consistency analysis of the entire scale, based on Cronbach's alpha coefficient, yielded a value of 0.76, indicating a satisfactory level of psychometric reliability. Regarding the subscales, two out of three demonstrated acceptable internal consistency ($\alpha > 0.70$, PS fit 0.88, PG fit 0.82), in accordance with the criteria proposed by George and Mallery (2016). In contrast, the PO fit subscale exhibited low reliability, with a Cronbach's alpha of 0.45.

A diagnostic survey method was employed in the research. The survey was conducted in December 2023 among a group of 250 soldiers. The structure of the research sample is presented in Table 2.

Table 2.
Structure of the research sample (N = 250)

Criterion	Answers	N	%
Gender	Female	22	8,80
	Male	228	91,20
Military Corps	Enlisted Personnel Corps	2	0,80
	Non-Commissioned Officers Corps	44	17,60
	Officers Corps	204	81,60
Age	18-30 age	37	14,80
	31-40 age	91	36,40
	41-49 age	77	30,80
	50 age and more	45	18,00
Length of Military Service	Up to 5 years	21	8,40
	6 to 10 years	40	16,00
	11 to 15 years	50	20,00
	16 to 20 years	40	16,00
	More than 20 years	99	39,60

Source: Author's research results.

The structure of the research sample revealed a predominance of male participants, primarily soldiers from the non-commissioned officer and officer corps, which prevents the sample from being considered representative.

4. Results

In analyzing the relationship between person-environment fit and job satisfaction, initial attention was directed toward satisfaction with military service. The results of the study indicate that 76% of soldiers reported feeling satisfied with their service, 4.8% expressed opposing views, and 19.2% found it difficult to provide a definitive assessment.

Subsequently, the analysis focused on three types of fit: person-supervisor, person-group, and person-organization. The distribution of responses across these dimensions is presented in Table 3.

Table 3.
Examined Types of Fit and Respondents' Opinions

Type of fit	Items	Strongly agree	Rather agree	Hard to say	Rather disagree	Strongly disagree
PS fit	I receive support from my supervisors in daily tasks	9,2	47,6	18,8	20	4,4
	My supervisor supports my professional development	17,27	38,55	19,68	17,27	7,23
	My supervisor is an authority to me	11,6	31,2	28,8	18,4	10

Cont. table 3.

PG fit	I receive support from my coworkers	21,6	56,0	16,8	4,8	0,8
	I trust my coworkers	20,4	59,2	12,4	6,8	1,2
PO fit	I am proud of serving in the military	56,4	36	6,8	0,8	0
	I fit into the military; this is the right workplace for me	38,96	44,18	12,85	3,21	0,80
	Military service is the fulfillment of my professional aspirations	28,51	40,56	21,29	8,03	1,61
	Serving in the military allows me to develop my passions	18	36,4	19,2	19,6	6,8

Source: Author's research results.

Focusing on interpersonal relationships, in the context of relations with supervisors, attention was given to support in daily tasks, support in professional development, and recognizing the supervisor as an authority figure. The study revealed that 56.8% of respondents received support from their supervisor in daily tasks. 55.82% indicated that their supervisor supports their professional development, and 42.8% recognized their supervisor as an authority. Regarding relationships with coworkers, 77.6% of respondents reported receiving support from their colleagues, while 79.6% declared trust in their coworkers.

Moving on to the analysis of person-organization fit, it is worth noting that the highest percentage of respondents (92.4%) expressed pride in serving in the military. 83.14% believed that they fit into the military and considered it the right workplace for them. 69.07% of respondents described military service as the fulfillment of their dreams, and 54.4% confirmed that the military allows them to develop their passions.

Analyzing the structure of responses, the highest number of positive evaluations was observed in the dimensions of person-organization and person-group fit, while the lowest was in the person-supervisor fit dimension.

To reveal statistical relationships between the studied variables, correlation coefficients were calculated separately for each fit dimension (see Tables 4, 5, and 6).

Table 4.
Relationship between PS fit and Job Satisfaction

Items	No.	1	2	3
I receive support from my supervisors in daily tasks	1			
My supervisor supports my professional development	2	0,71***		
My supervisor is an authority to me	3	0,65***	0,72***	
I experience satisfaction with my military service	4	0,24*	0,39***	0,31***

Note: *p < 0,05, **p < 0.01, ***p < 0,001.

Source: Author's research results.

The conducted analyses confirmed statistical relationships between all examined variables within the dimension of Person-Supervisor (PS) fit. The revealed relationships were positive in nature. The strongest correlations were observed between the variables: "My supervisor is an authority to me" and "My supervisor supports my professional development" (0.72), as well

as “I receive support from my supervisors in daily tasks” and “My supervisor supports my professional development” (0.71).

In the second analyzed dimension person-group fit, two statements were examined (see Table 5).

Table 5.
Relationship between PG fit and Job Satisfaction

Items	No.	1	2
I receive support from my coworkers	1		
I trust my coworkers	2	0,70***	
I experience satisfaction with my military service	3	0,30***	0,30***

Note: *p < 0,05, **p < 0.01, ***p < 0,001.

Source: Author’s research results.

The analysis of the conducted research indicates that trust in colleagues is strongly correlated with receiving support from them (r = 0.70). Additionally, a weak relationship was confirmed between two dimensions of fit within the person-group domain and job satisfaction (both correlations at the level of r = 0.30).

The results of the analysis concerning the third dimension under investigation are presented in Table 6.

Table 6.
Relationships between Person-Organization Fit and Job Satisfaction

Items	No.	1	2	3	4
I am proud of serving in the military	1				
I fit into the military, this is the right workplace for me	2	0,44***			
Military service is the fulfillment of my professional aspirations	3	0,43***	0,59***		
Serving in the military allows me to develop my passions	4	0,35***	0,52***	0,54***	
I experience satisfaction with my military service	5	0,55***	0,55***	0,60***	0,55***

Note: *p < 0,05, **p < 0.01, ***p < 0,001.

Source: Author’s research results.

The strongest relationship was identified between the variables: “I fit into the military, this is the right workplace for me,” and “Military service is the fulfillment of my professional aspirations” - with a moderate correlation strength of 0.59. Only in the case of variables related to pride in military service and the development of personal passions was a weak correlation observed (0.35).

When examining the relationship between job satisfaction and the analyzed variables, the highest correlation strengths were found within the person-organization fit dimension. A strong correlation was revealed between “Military service is the fulfillment of my professional aspirations” and job satisfaction (r = 0.60; p < 0.001), along with moderate correlations between “I am proud of serving in the military”, “I fit into the military, this is the right workplace for me”, and “Serving in the military allows me to develop my passions” (r = 0.55).

The second dimension, person-supervisor fit, showed weaker correlations, with the strongest relationship in this area observed between "My supervisor supports my professional development" and job satisfaction (r = 0.39). In contrast, person-group fit revealed a weak correlation between the variables (r = 0.30).

5. Discussion

The conducted research on person-environment fit (PE fit) in the context of military service demonstrated that person-organization fit plays a pivotal role in shaping soldiers' satisfaction with service. The findings confirm the possibility of establishing a hierarchy of importance among the various dimensions of fit, highlighting the significance of person-organization fit, particularly in terms of value and identity alignment, i.e., the congruence between individual values and organizational culture.

A high level of service satisfaction, declared by 76% of soldiers, can be interpreted both as an expression of organizational commitment and as an indicator of the durability of the relationship between soldiers and the military as their workplace. Trust and support from colleagues and supervisors also proved to be significant, underscoring the importance of nurturing interpersonal relationships within the work environment. A strong correlation between the fulfillment of professional aspirations and satisfaction with service (0.60) suggests that the realization of personal career goals is a key factor influencing soldiers' occupational well-being.

The findings indicate that person-organization fit plays a more significant role in shaping satisfaction with military service than person-supervisor or person-group fit. From the perspective of interpersonal relationships, the person-supervisor dimension appears to be more influential than person-group fit. The findings indicate that the quality of interpersonal relationships between commander and soldier can be assessed as positive and constructive. Recognizing the supervisor as an authority figure, receiving support in daily tasks, and in professional development are indicators of fit within the analyzed dimension. Additionally, the study revealed a statistically significant, albeit weak, relationship between various dimensions of person-supervisor fit and satisfaction with service. The research findings therefore correspond with the views of Wheeler et al. (2005), who stated that individual preferences or environmental cues may cause certain fit dimensions to become more salient than others. Additionally, as confirmed by Kristof-Brown and Guay (2011), identifying the reasons why certain fit dimensions are perceived as more salient is a crucial issue, especially now that the multidimensionality of person-environment fit (PE fit) has been recognized. Therefore, further research in this area is warranted.

These results should be considered in light of the findings by Deschênes (2021), who identified person-group fit as the key dimension of fit for Generation Y employees. However, the present study contradicts this conclusion, which may be explained by the specific characteristics of the research group - professional soldiers. While the person-group dimension was acknowledged as important, person-supervisor fit was rated as more significant by the participants.

In the context of the broader concept of military service and the importance of vocational calling, the findings confirm that this sense of calling - understood as the fulfillment of professional aspirations and the belief in fitting into the organization - reinforces the relevance of person-organization fit.

It is also justified to emphasize that the obtained Cronbach's alpha coefficient for the PO fit subscale ($\alpha = 0.45$) indicates a low level of reliability, which may suggest limited internal consistency among the items comprising this subscale. Despite the low reliability, it is worth considering further exploratory research on the PO fit construct, taking into account the possibility of its redefinition or expansion with additional components that could enhance internal consistency.

Additionally, as emphasized throughout the article, longitudinal studies are recommended to analyze changes in fit and satisfaction over time. It is also advisable to examine both subjective and objective measures of fit, including complementary and supplementary fit, to gain a more comprehensive understanding of the phenomenon.

6. Conclusions

The findings contribute significantly to the development of knowledge on person-environment fit in the context of military service. They confirm the greater importance of person-organization fit compared to person-supervisor or person-group fit, which contradicts previous conclusions regarding Generation Y employees (Deschênes, 2021). This discrepancy may be explained by the specific characteristics of the professional soldier group, for whom the relationship with the supervisor and the organizational structure are of relevance. The data obtained may be used in further research on fit in hierarchical environments and in human resource management practices within uniformed institutions.

Despite the valuable findings, the study has several notable limitations. Most importantly, the research sample consisted primarily of officers of the Polish Armed Forces, which restricts the generalizability of the results to the broader population of professional soldiers, including non-commissioned officers and privates. Additionally, the low reliability of the person-organization fit (PO fit) subscale, indicated by a Cronbach's alpha coefficient of 0.45,

may suggest limited internal consistency among the items comprising this part of the instrument, warranting further methodological reflection.

The study provided important insights into the factors influencing satisfaction with military service. The high level of declared satisfaction (76%) may be interpreted as an expression of organizational commitment and the durability of the relationship between the soldiers and the military institution. The strong correlation between the fulfillment of professional aspirations and satisfaction with service ($r = 0.60$) indicates that achieving career goals plays a key role in soldiers' occupational well-being.

The conclusions drawn from the study are clearly and unambiguously linked to the results and highlight the need for further exploration of the person-organization fit construct, particularly in terms of its operationalization and measurement. Theoretical implications point to the necessity of considering occupational specificity in fit analyses, while practical implications emphasize the importance of supporting career aspirations and interpersonal relationships to enhance job satisfaction. It is also justified to stress the need for longitudinal studies and the inclusion of both subjective and objective measures of fit, which would allow for a more comprehensive understanding of this complex phenomenon. Such research may contribute to the development of effective human resource management strategies in the military, aimed at supporting professional development and well-being, as well as enhancing satisfaction with service. Broad-based studies may also reveal potential generational differences in fit, aligning with the military's need to identify and understand the impact of generational diversity on service dynamics and perceptions of the military's attractiveness as an employer.

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CONFIGURATIONAL PATHS TO SUCCESSFUL DIGITAL TRANSFORMATION

Anna KWIOTKOWSKA

Silesian University of Technology; akwiotkowska@polsl.pl, ORCID: 0000-0001-5204-1259

Purpose: Digital transformation has emerged as a strategic priority fostering the advancement of high-quality small and medium-sized enterprises (SMEs). However, existing research provides only limited and fragmented insights into the underlying components that determine digital success within SMEs. The purpose of this study is to identify the key factors shaping the digital transformation process in SMEs and to explore effective paths for their successful digital adaptation.
Design/methodology/approach: The study was conducted using the fuzzy-set Qualitative Comparative Analysis (fsQCA) method, which was applied to a sample of 56 small and medium-sized enterprises (SMEs) in order to identify the key configurational paths leading to successful digital transformation.
Findings: The findings indicate that the success of digital transformation in SMEs is not driven by a single factor but rather emerges from the adaptive interplay of multiple variables. Five main paths to successful digital transformation in SMEs were identified. A comparative analysis of these paths reveals substitutive effects among certain drivers of digital transformation.
Originality/value: This study advances the understanding of the antecedents of digital transformation in SMEs by uncovering the complex causal relationships among influencing factors. At the same time, it provides practical insights and guidance for enterprises pursuing digital transformation initiatives.
Keywords: digital transformation, configurations, fuzzy set qualitative comparative analysis, necessary condition analysis, SMEs.
Category of the paper: research paper.

1. Introduction

The swift progress and broad diffusion of emerging digital technologies, such as cloud computing, big data, and the Internet of Things have reshaped the global competitive environment, stimulated the growth of the digital economy, and propelled industries across the world toward digital transformation. Digital transformation refers to the process through which firms employ digital technologies to reconfigure business models and operational practices,

thereby improving efficiency, generating new revenue opportunities, enhancing customer engagement, and strengthening overall competitiveness (Meier et al., 2025). For SMEs, digital transformation has become a critical requirement for enhancing operational efficiency, reducing costs, and strengthening competitive advantage. At the same time, policy support and evolving market demands are driving these firms toward digitalization, equipping them with tools to better address challenges and adapt to shifting market conditions (Yin, Zhao, 2024). Nevertheless, the digital transformation of SMEs remains marked by gaps and disparities, as well as considerable variation in digital maturity across different industries (Omrani et al., 2022). SMEs face a range of barriers, including limited technological infrastructure, a shortage of specialized digital competencies, difficulties in precisely identifying transformation needs, and the absence of unified standards. These factors often result in fragmented, inconsistent, and disorganized transformation processes. An additional challenge stems from the slow returns of digital initiatives, which cause many SMEs—despite their willingness to embrace change—to delay implementation due to uncertainty and risk aversion. A key obstacle is also the lack of in-depth knowledge about their internal capabilities, which prevents firms from developing digital transformation strategies tailored to their specific characteristics. This study aims to support SMEs in identifying digital transformation pathways suited to their individual conditions, thereby enabling them to achieve intended transformation goals through diverse and customized approaches.

Methodologically, most existing research on the digital transformation of SMEs relies on descriptive qualitative analyses or traditional linear regression and econometric methods to assess how individual factors influence the transformation process. However, such approaches fail to fully capture the complex interdependencies among the multiple determinants shaping digitalization (He et al., 2023; Kwiotkowska, 2024). Digital transformation in SMEs is in fact driven by the interplay of interconnected elements, including technological capabilities, market dynamics, and institutional support. Examining these factors in isolation risks oversimplifying the critical synergies necessary for successful and sustainable transformation. This limitation in the current literature highlights a significant research gap: the need for a comprehensive understanding of how diverse factors interact and reinforce one another in driving digital transformation within the SME sector.

This study seeks to address the following research questions:

RQ1: What are the key technological, organizational, and environmental factors influencing the digital transformation of SMEs?

RQ2: How do these factors interact with one another and, in combination, configurationally shape the digital transformation of SMEs?

RQ3: What pathways lead to successful digital transformation?

This study examines the complex interactions between technological, organizational, and environmental factors to assess their configurative impact on the digital transformation of SMEs. Applying this framework to SME digital transformation, this study aims to demonstrate

how these factors converge to drive or constrain SME digital development. This approach advances this area of research, which remains underexplored in the literature. Unlike traditional research approaches, this paper employs fs/QCA to analyze the digital transformation of SMEs, enabling the exploration of multidimensional factor interactions, the identification of necessary conditions, the tracing of the stepwise nature of transformation, and the clarification of the relationship between resources and market dynamics, as well as the recognition of equivalent transformation pathways. By combining in-depth qualitative insights with rigorous quantitative analysis, fs/QCA provides a powerful lens through which to understand the complexity of digital transformation, advancing both theoretical frameworks and practical implications in the SME context.

It is important to emphasize that, from a configurational perspective, this study examines the complex causal interactions among multiple factors and their influence on the outcomes of digital transformation. This approach provides a more comprehensive understanding of the paths and mechanisms of transformation, offering new theoretical insights to the literature on SME digital transformation. Furthermore, the findings provide both theoretical contributions and practical recommendations for SMEs pursuing digital transformation. From a practical standpoint, SMEs are encouraged to adopt transformation strategies tailored to their specific circumstances and resource constraints, rather than replicating the approaches of larger firms. Such a customized approach enables SMEs to more effectively identify and capitalize on digital opportunities, thereby enhancing their flexibility and adaptive capacity in response to evolving market dynamics (Merin-Rodriganez et al., 2024).

The structure of this paper is as follows: it first outlines the theoretical foundations followed by a detailed description of the data and methodological approach. The subsequent section presents the empirical findings along with their interpretation. The paper concludes with a synthesis of the main contributions, practical implications, and directions for future research.

2. Literature review

Digital transformation refers to significant organizational changes driven by the integration of information, computing, communication, and networking technologies, which enhance business processes (Vial, 2019). So far, research in the literature has mainly focused on internal factors, such as: technological capabilities, human resources, and knowledge (Stief et al., 2016), leadership, organizational culture, employee and partner engagement, alignment of business and IT strategies, process standardization, data integration, employee training and skills development, agile change management, and the use of both internal and external knowledge (Cichosz et al., 2020). Studies also emphasize the role of mechanisms of influence, including:

changes in management structures (Steiber et al., 2021), the development and adoption of technologies (Vial, 2019), innovative organizational integration (Hanelt et al., 2021).

It is important to note that SMEs tend to adopt digital transformation more slowly than large enterprises. This often happens because decisions are made reactively, under pressure from emerging technologies in the industry (Rochet, Tirole, 2008). As a result, many SMEs introduce digital transformation mainly to ensure survival and remain competitive. Another relevant factor is the level of regional digital development, which serves as an incentive for organizations to adopt changes. Government policies promoting digital innovation in SMEs play a particularly important role here (Ramdani et al., 2022).

Nevertheless, most existing studies on digital transformation remain descriptive in nature. There is a lack of empirical analyses that examine the specific conditions of digitalization in SMEs. The mechanisms underlying the choice of transformation pathways remain unclear, and understanding the complex cause-and-effect relationships between variables and their configurations is still limited. Therefore, it is essential to investigate the configurations of factors and transformation paths that enable SMEs to achieve successful digital transformation.

This study adopts a theoretical framework based on the idea that the adoption and use of innovative technologies in organizations are influenced by three factors: technology, organization, and environment. Technological factors refer to the characteristics and properties of technologies relevant to the functioning of an enterprise, encompassing both the solutions already implemented and those available on the market but not yet adopted (Baker, 2012). Organizational factors capture the influence of managerial conditions, including firm-specific attributes and resources such as organizational size and structure, business profile, internal communication processes, and the extent of slack resources (Zhu et al., 2006). In turn, environmental factors concern the uncertainty of the external environment, arising from elements such as industry structure, relationships with suppliers, and market scope (Barker et al., 2022).

As digital transformation processes deepen and digital technologies evolve rapidly, the business environment and management information systems become increasingly complex. Within this context, the three key perspective: technological, organizational, and environmental interact in a coordinated manner, shaping firms' innovation capabilities and performance outcomes. Consequently, examining the drivers of digital transformation solely through the lens of a single factor, such as resources or capabilities, risks oversimplification. A more comprehensive understanding requires investigating multi-factor configurations that influence the choice of transformation paths and underlie higher rates of success in digitalization efforts.

The technological perspective encompasses both the technological innovation capability and the quality of digital infrastructure. For SMEs, strengthening innovation capabilities fosters the development of new products and services while simultaneously enhancing operational efficiency. Equally important is the expansion of modern digital infrastructure and the adoption of advanced solutions such as data analytics, cloud computing, the Internet of Things,

and artificial intelligence. These technologies enable firms to acquire external knowledge, reduce information asymmetry between supply and demand, improve internal knowledge flows, and ultimately increase the effectiveness of digital transformation processes (Chang et al., 2019). Conversely, SMEs with outdated digital infrastructures face considerable pressure to modernize in order to meet contemporary business requirements. Such modernization not only enhances operational efficiency but also reinforces competitive positioning. As a result, this pressure serves as a critical driver of digital transformation, allowing SMEs to adapt and grow in an increasingly dynamic market environment.

The organizational perspective encompasses two key elements: digital strategy and risk resilience. Digital strategy is one of the key driving forces behind the transformation and modernization of enterprises. By defining an organization's vision, strategic priorities, and directions for development, it structures and standardizes the process of change (Correani et al., 2020). Formulating a clear concept of digital transformation—based on well-defined objectives and realistic action plans—is a necessary prerequisite for initiating modernization efforts, as it provides the company with a coherent and well-directed development path (Proksch et al., 2021). Risk resilience, defined as the capacity to adapt to uncertainty and external disruptions, has become a key driver of digital transformation. SMEs, often facing unstable environments, need to strengthen this capability to overcome barriers in their digitalization processes. Prior studies show that resilience is positively associated with successful digital transformation (Wang, Chen, 2022), while low resilience hampers broader business change (Chen et al., 2023). Thus, effective risk management is essential for ensuring sustainable digital initiatives.

The environmental perspective comprises government support and market competitiveness. Government support plays a vital role in advancing digital transformation by easing financial constraints, reducing risks, and enhancing firms' confidence in digital initiatives. By providing external intervention and regulatory guidance, public authorities help enterprises accelerate ecosystem development and adopt standardized digital modernization practices (Wang et al., 2019). In the context of advancing digitalization, capital markets increasingly reward industries characterized by a high level of technological sophistication and superior profitability, while rising consumer expectations regarding product and service quality further intensify competitive pressures (Barker et al., 2022). At present, both market standing and competitive strength represent critical determinants of a firm's readiness to pursue innovation and transformation. Enterprises with stronger competitive positions are generally more inclined to leverage digital transformation as a strategic tool to reinforce their advantage in uncertain market environments.

To conclude, a research model has been developed and illustrated in Figure 1.

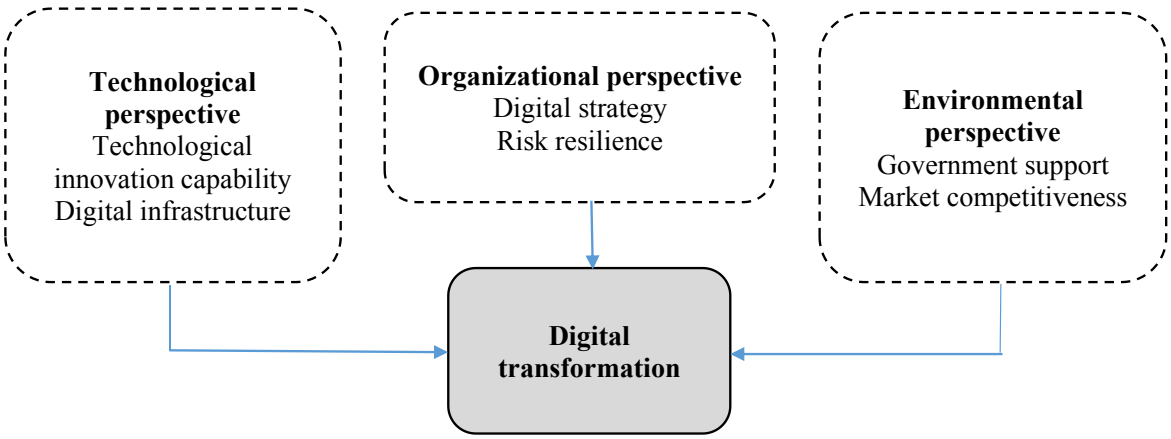


Figure 1. Research model.

Source: own study.

The research model presented in Figure 1 integrates the technological, organizational, and environmental dimensions that jointly determine the digital transformation processes of SMEs. It demonstrates that successful digital transformation results not from isolated factors, but from the interdependence and alignment of multiple conditions that together shape firms' ability to adapt, innovate, and compete in a dynamic market environment.

Accordingly, the model serves as a conceptual basis for further empirical investigation into the specific configurations of factors that enable SMEs to achieve effective digital transformation. It provides a structured framework for examining how various internal and external determinants interact to influence strategic decisions, innovation capacity, and performance outcomes. By adopting this multidimensional perspective, the study contributes to a more comprehensive understanding of the mechanisms underlying digital transformation in small and medium-sized enterprises.

3. Methods

In this study, a configurational approach was applied to analyze the determinants of successful digital transformation in the SME sector. This perspective is based on three key assumptions. First, digital transformation is the result of complex interactions between three perspective of a company's operations: technological, organizational, and environmental. Accordingly, the study employs the QCA method, which unlike traditional regression models that focus on the influence of individual variables, enables the identification of synergistic effects arising from combinations of multiple factors and reveals the mechanisms leading to effective digital transformation. This approach is particularly well-suited for exploring intricate complex causal relationships (Pappas, Woodside, 2021). Second, it is important to emphasize that the determinants of transformation processes do not function in isolation but are

interconnected in various configurations. The principle of equifinality, which is characteristic of QCA, allows for the examination of multifactorial dependencies and the identification of different pathways leading to the same outcome. Third, due to the partial nature of membership in both the causal and outcome conditions, classifying them in binary categories ("0" and "1") would be insufficient. Therefore, fuzzy-set qualitative comparative analysis (fs/QCA) was used, which makes it possible to study combinations of resources and capabilities in a way that reflects the varying intensity of individual conditions. This approach captures important differences in the strength of factor influence and thereby provides a more precise explanation of the mechanisms leading to successful digital transformation in SMEs. In this study, version 3.0 of fs/QCA for Windows (Ragin, Davey, 2016) was used.

A structured survey questionnaire was developed based on a comprehensive review of prior literature, ensuring high content validity. In the initial stage, the reliability of the instrument was tested on a pilot sample of 39 respondents representing ten SMEs. To explore the three key dimensions of business operations: technological, organizational, and environmental, that are essential to the digital transformation process, data were collected from Polish SMEs currently undergoing digital transformation and possessing relevant experience. The automotive industry was selected for this study due to its pioneering role in adopting innovative digital technologies and its superior technological infrastructure compared to other sectors (Schuh et al., 2017). Data collection was carried out in 2024 and targeted middle and senior-level managers from 56 small and medium-sized enterprises in Poland. A total of 113 completed questionnaires were initially obtained. However, to ensure data quality, incomplete or empty responses were excluded from the final dataset. Consequently, 73 fully completed questionnaires were included in the analysis. The basic characteristics of the research sample are presented in Table 1.

Table 1.
Basic characteristics of the research sample

Content	Proportion
The stage of the companies' development	
Start-up period	9.6
Growth period	38.4
Maturity period	49.4
Scale of enterprises	
Micro companies	17.3
Small companies	38.8
Middle companies	43.9
Respondent's position in the company	
Manager	29.3
Senior Manager	43.7
Executive (CEO, CMO, CFO, CIO)	27
Respondent's period of employment in the company	
5 years	8.2
6-10 years	18.9
11-15 years	46.8
More than 15 years	26.1

Source: own study.

The survey questionnaire employed a 7-point Likert scale to measure each item, where 1 indicated complete disagreement and 7 indicated full agreement. To ensure the validity of the study, established and validated measurement scales were applied. Specifically, the scale for assessing digital transformation was adopted from AlNuaimi et al. (2022). Within the technological perspective, technological innovation capability and digital infrastructure were assessed using the scales developed by Liu and Xie (2020) and Nambisan et al. (2017), respectively. Regarding the organizational perspective, resilience to risk was measured with the scale proposed by Nguyen et al. (2023), while digital strategy was evaluated using the instrument of AlNuaimi et al. (2022). Finally, for the environmental perspective, government support was captured through the scale of Wang et al. (2019), whereas market competitiveness was measured following the approach of Nguyen, Pham, et al. (2023).

In order to evaluate the reliability of the measurement instruments, Cronbach's alpha coefficients were calculated. The obtained values were 0.87 for digital transformation, 0.85 for technological innovation capability, 0.83 for digital infrastructure, 0.92 for digital strategy, 0.84 for resilience to risks, 0.89 for government support, and 0.82 for market competitiveness. Since all coefficients exceeded the recommended threshold of 0.70, the scales employed in this study can be considered reliable.

4. Results

The first step in the fs/QCA procedure involves calibrating both the outcome variable and the causal conditions to determine their fuzzy set membership scores. In this study, the direct calibration method was employed, and the calibration function in fs/QCA 3.0 software was used to transform the raw data into membership values within the [0,1] interval. For each variable, the mean score was calculated and treated as its final value. Following established calibration standards, the thresholds were set at the 95th percentile for full membership, the 50th percentile for the crossover point, and the 5th percentile for full non-membership. The specific calibration anchors for each variable are reported in Table 2.

A necessity analysis was conducted for the antecedent conditions and their negations across different modes of transformation in order to mitigate the risk of omitting necessary conditions in the parsimonious solution. The results of this analysis, obtained using fsQCA 3.0 software, are presented in Table 3. According to the established criterion that the consistency level of a necessary condition must exceed 0.90, none of the variables examined in this study qualified as a necessary condition for digital transformation.

Table 2.
Calibration anchors of each fuzzy set

Sets		Calibration anchors		
		Fully in	**Crossover**	**Fully out**
Digital transformation		5.8	4.9	1.5
Technological	Technological innovation capability	6	4.8	1.5
	Digital infrastructure	6	5	1.5
Organizational	Resilience to risk	5.9	4.75	1.5
	Digital strategy	5.7	4.8	1.5
Environmental	Government support	6	4.7	1.5
	Market competitiveness	5.75	4.9	1.5

Source: own study.

Table 3.
Analysis of necessity for digital transformation

Conditions	High digital transformation	
	consistency	**coverage**
Technological innovation capability	0.51	0.54
~Technological innovation capability	0.84	0.80
Digital infrastructure	0.58	0.58
~Digital infrastructure	0.81	0.81
Resilience to risk	0.57	0.56
~Resilience to risk	0.79	0.82
Digital strategy	0.51	0.56
~Digital strategy	0.86	0.55
Government support	0.52	0.84
~Government support	0.81	0.57
Market competitiveness	0.54	0.56
~Market competitiveness	0.79	0.83

Source: own study.

To reduce potential contradictory configurations and possible subset relations, the empirical data in this study were analyzed using fsQCA 3.0, with the PRI threshold set at 0.8 and the minimum frequency of cases set at 1. In the standardized truth table analysis the "present or absent" option was selected to generate the intermediate solution. Following established methodological conventions, antecedent conditions that appeared in both parsimonious and intermediate solutions were classified as core conditions, whereas those that appeared only in intermediate solutions were identified as peripheral conditions. The detailed results of the configurational analysis are presented in Table 4.

Table 4.
Sufficient configurations for digital transformation

Solutions	Sets	Raw Coverage	Unique Coverage	Consistency
S1a	**Digital infrastructure*Technological innovation capability***Government support***Market Competitiveness**	0.95	0.10	0.91
S1b	**Digital infrastructure*** Resilience to risk***Technological innovation capability***Digital strategy***Market Competitiveness**	0.37	0.08	0.94
S2a	**Digital infrastructure***Digital strategy***~Government support**	0.34	0.07	0.92

Cont. table 4.

S2b	**Digital infrastructure*~Government support***~Market competitiveness	0.23	0.03	0.91
S2c	**Digital infrastructure***Technological innovation capability*~Resilience to risk***~Government support**	0.31	0.05	0.91
Overall solution coverage: 0.58				
Overall solution consistency: 0.91				

Note:
- * logical AND; ~logical negation.
- bold indicates core conditions, while no bold indicates peripheral conditions.

Source: own study.

As shown in Table 4, different combinations of antecedent conditions generated five configurations leading to successful digital transformation. Each configuration demonstrated a solution consistency of 0.91, 0.94, 0.92, 0.91 and 0.91, respectively, all exceeding the threshold of 0.90, thereby confirming their sufficiency for achieving a high level of digital transformation in enterprises. Furthermore, these configurations were classified into two distinct configuration paths, differentiated on the basis of core conditions.

In highly competitive market environments, configuration S1a indicates that firms may attain successful digital transformation even in the absence of risk resilience or a formally articulated digital strategy, as long as they exploit the complementary effects of digital infrastructure, technological innovation capability, and governmental support. This path explains 95% of advanced digital transformation cases among the analyzed SMEs, with 10% of cases being uniquely attributable to this configuration.

Configuration S1b suggests that within highly competitive markets, enterprises may still realize successful digital transformation by reinforcing digital infrastructure, enhancing technological innovation capability and market competitiveness, and adopting a comprehensive digital strategy underpinned by risk resilience, regardless of financial support from government sources. This pathway accounts for 37% of successful digital transformation cases among SMEs, with 8% uniquely explained by this configuration.

Configuration S2a highlights that, for companies operating without government support, improving their digital infrastructure and strategic digital planning can collectively enhance digital transformation. This path indicates that companies without explicit government support or policy incentives benefit from adopting a proactive approach, transforming their organizational models, and implementing advanced technologies to strengthen digital capabilities. The configuration's consistency is 0.92, and the coverage is 0.34, indicating that this path accounts for 34% of digital transformation cases among SMEs.

Configuration S2b demonstrates that for enterprises lacking government support but operating in markets with low competitiveness, strengthening digital infrastructure alone can drive successful digital transformation. In this path, digital infrastructure plays a pivotal role, accounting for approximately 23% of successful digital transformation cases among SMEs.

In configuration S2c, enterprises constrained by insufficient risk resilience and the absence of government subsidies can still achieve advanced digital transformation by enhancing digital infrastructure and developing strong technological innovation capabilities. This path accounts for approximately 31% of high-level digital transformation cases among SMEs. The differences between configurations S2a and S2c highlight the substitutability of digital strategy and technological innovation capability as conditional factors. In the case of configuration S2c, enterprises can partially offset the lack of government support by strengthening their technological innovation capability, thereby effectively managing transformation-related uncertainty.

To assess the robustness of the findings, a set-theoretic approach with a high degree of methodological rigor was employed. Robustness was examined by adjusting both the calibration thresholds and the consistency cutoff level. Specifically, the 90th and 10th percentiles of the sample distribution were used as benchmarks for full membership and full non-membership, respectively, while the consistency threshold was modified by ±0.5. The analysis considered potential changes in the number of configurations, their composition, as well as associated consistency and coverage parameters. The results of these robustness checks revealed no significant variations across these dimensions, thereby confirming the stability and reliability of the study's outcomes.

5. Discussion and conclusions

In this study, the fs/QCA method was applied to examine the synergistic effects and equifinal paths through which factors from three perspectives: technological, organizational, and environmental jointly enhance digital transformation in SMEs. The entire research process was framed within a holistic configurational perspective. The primary aim of this study is to identify the key determinants shaping the digital transformation of SMEs and to investigate effective paths that facilitate their successful digital adaptation. The main results can be summarized as follows:

First, the success of digital transformation does not stem from the isolated impact of a single factor but rather from the convergence of complex interactions among multiple internal and external determinants. The analysis demonstrates that none of the conditions within the technological, organizational, or environmental dimensions alone constitutes a necessary prerequisite for achieving an advanced level of digital transformation. These findings align with the results of Song, Chen, and Gu (2023), who emphasize that the combined influence of multiple factors significantly outweighs the effect of any single determinant. By examining the sufficiency of different configurations, the study identified five alternative combinations leading to high levels of digital transformation, thereby illustrating the principle of "multiple

paths to the same outcome." Based on core conditions, these configurations can be further classified into two main types: (1) high technological innovation capability coupled with strong digital infrastructure under conditions of intense market competitiveness (configurations S1a and S1b), and (2) robust digital infrastructure compensating for the absence of government support (configurations S2a, S2b and S1c).

Second, the analysis of the five configurations leading to successful digital transformation reveals the presence of substitution effects, whereby certain elements can act as interchangeable drivers of transformation outcomes. For instance, enterprises equipped with advanced digital infrastructure and strong technological innovation capabilities may enhance the level of their digital transformation either by obtaining government subsidies and institutional support or by strengthening risk resilience and formulating an appropriately aligned digital strategy. This finding is consistent with the study of Chen and Tian (2022), who identified a substitutive relationship among the drivers of digital transformation. Furthermore, in contexts where government support is limited, firms can advance digital transformation not only through the development of digital infrastructure but also by pursuing strategic positioning, formulating coherent digital strategies, and reinforcing their technological innovation capabilities.

Third, the identified configurations reveal that digital infrastructure, technological innovation capability, and market competitiveness constitute the primary drivers of digital transformation in SMEs. These factors operate synergistically with other conditions, further underscoring that successful digital transformation is not the outcome of isolated determinants. Moreover, the findings, particularly configurations S2a, S2b, and S2c, indicate that government support does not represent a key condition for advancing digital transformation among SMEs. This conclusion is consistent with the results of Nguyen et al. (2023), who demonstrated that internal technological factors, such as IT infrastructure, together with organizational elements, including specific skills and resources, play a more decisive role in enabling digital transformation than external governmental interventions. While public policy and subsidies may enhance SMEs' confidence in pursuing digitalization, the effective implementation of digital transformation strategies fundamentally depends on the development of digital talent, the strengthening of technological innovation capabilities, and the reinforcement of core market competitiveness.

This study offers several important theoretical contributions to the literature on digital transformation. First, it develops a comprehensive analytical framework that enables the identification of complex causal mechanisms underlying the digitalization of SMEs, thereby enriching the understanding of their developmental trajectories and transformation processes. Second, by applying the fs/QCA method, the research captures the interplay of multiple concurrent conditions, providing a multidimensional perspective on the determinants of digital transformation success. In line with the findings of Jia et al. (2024), the analysis highlights the central role of digital infrastructure as a critical enabler of successful transformation. Moreover, the results emphasize the significance of building strong technological innovation capabilities

and point to market competitiveness as a powerful catalyst that accelerates firms' digital initiatives. Third, the research model further enables the identification of multiple configurations that drive digital transformation success, underscoring that the process is not uniform but can be realized through various distinct paths.

This study also offers practical implications for SME management. Managers should focus on streamlining business processes, setting clear and measurable goals for digital transformation, developing appropriate digital platforms, making data-driven decisions, and ensuring integration within the broader digital ecosystem. The findings indicate that consistent managerial commitment to digital initiatives is essential for successful transformation. It is crucial for managers to prioritize strategies that enable the digitalization of both organizational and operational processes, while also fostering alignment and synergy between digital technologies and core business functions. This integrated approach can significantly enhance overall organizational performance.

Despite providing valuable insights, this study is not without its limitations. The proposed research model incorporated a limited number of variables, which narrows the scope of the analysis. Future studies could expand the model by including a broader range of factors influencing digital transformation, drawing from diverse theoretical frameworks and research perspectives. Additionally, the empirical investigation focused exclusively on a small number of SMEs operating in Poland. Subsequent research could broaden the geographical scope to include firms from other countries, a larger sample size, and a mix of organizational types, including large corporations. Given the dynamic and ongoing nature of digital transformation, it is also important to explore this process as it evolves over time. The application of time-series QCA could offer deeper insights into how different configurations of conditions influence digital transformation in a temporal context. Moreover, future research could investigate the role of governments in enhancing the monitoring and management of environmental impacts, particularly with regard to improving transparency in carbon footprint reporting (Yin, Zhao, 2024).

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FACTORS MOTIVATING THE ENHANCEMENT OF DIGITAL COMPETENCES IN AGILE ORGANIZATIONS

Magdalena MACIASZCZYK[1], Maria KOCOT[2*], Artur KWASEK[3]

[1] Lublin University of Technology; m.maciaszczyk@pollub.pl, ORCID: 0000-0001-7225-4921
[2] University of Economics in Katowice; maria.kocot@ue.katowice.pl, ORCID: 0000-0001-5150-3765
[3] Vistula University in Warsaw; a.kwasek@vistula.edu.pl, ORCID: 0000-0003-4386-1444
* Correspondence author

Purpose: The purpose of the study was to identify the key motivational factors influencing employees' decisions to enhance their digital competences in agile organizations and to examine the interrelationships between these factors. The study aimed to determine which motivators play the most important role in fostering continuous digital development.
Design/methodology/approach: The research was conducted using a survey method on a sample of 525 respondents in 2025. Pearson's correlation coefficients were calculated to assess the strength and direction of relationships between individual motivational factors.
Findings: The results showed that developmental, professional, material, and life situation factors are the strongest motivators for raising digital competences, while social affiliation plays a significantly weaker role.
Research limitations/implications: The cross-sectional nature of the study did not allow for observation of changes over time, and the results are based on self-reported declarations, which may reflect subjective perceptions. The findings should therefore be interpreted within the context of the studied sample, with caution in generalizing them to other groups.
Practical implications: The study highlights the importance of creating organizational environments that strongly support developmental and material aspects, such as transparent career paths, financial incentives, and access to digital training. Agile organizations can enhance employee engagement and digital skill development by focusing on these areas.
Social implications: Strengthening digital competences contributes to greater adaptability of employees and increases their employability, which in turn supports broader social goals such as digital inclusion and workforce resilience in the face of technological change.
Originality/value: The study provides new insights into the motivational structure behind digital competence development in agile organizations, emphasizing the interplay of developmental, professional, and material factors. It offers empirical evidence of how these motivators interact and jointly shape employees' readiness for digital transformation.
Keywords: digital competences, motivating factors, agile organizations, organization, communication.
Category of the paper: research paper.

1. Introduction

The dynamic development of technology and the ongoing digital transformation make digital competences an indispensable element of the functioning of modern organizations. This is especially true for agile organizations, as they need to demonstrate flexibility, adaptability and readiness to innovate. Analysis and understanding of the factors motivating employees to improve IT competences takes on an integral meaning. It allows for better shaping development strategies and supporting digitization processes in the workplace (Kocot, Kwasek, Radowicki, Gontarek, Oleksiejuk, 2025; Rouhan, 2025).

The article includes a theoretical part, which was devoted to the problem of the concept of agile organizations and the role of digital competences. Next, the results of empirical research conducted on a sample of 525 employees were presented. The analysis is focused on assessing the importance of individual motivational factors and determining the relationship between them. The study culminates in a discussion on the results obtained, their reference to the literature on the subject and the indication of recommendations for practice.

The aim of the article is to identify and analyze the factors conducive to the development of digital competencies in agile organizations. The added value of the work lies in showing that developmental, professional and material factors are the central element of motivation, and their interconnections create a coherent system supporting the process of digitization and organizational adaptation.

Despite the growing number of studies on digital competences in agile organizations, there is still a noticeable research gap related to understanding which specific motivational factors most strongly determine employees' willingness to develop these competences. Previous works have often addressed either general aspects of digital transformation or the role of organizational agility, but they rarely combined these perspectives to examine the direct interrelations between developmental, professional, material, and social factors. The novelty of this study lies in filling this gap by providing empirical evidence on the mutual dependencies of these motivators and showing how they jointly shape employees' readiness for digital transformation in agile organizations.

1.1. The concept of agile organizations

The concept of agile organizations is a consequence of the need to respond flexibly to the dynamically changing conditions of the economic and technological environment. Organizational agility is understood as the ability to quickly adapt to new conditions, take advantage of emerging opportunities, and minimize the risk associated with market uncertainty and volatility (Holbeche, 2023; Harvey, De Meuse, 2021). This concept is based on the belief that in order to maintain a competitive advantage, organizations must be open to change, have the ability to learn quickly, and be willing to innovate (Bresciani, Ferraris,

Romano, Santoro, 2021). In this approach, the understanding of organizational agility as a one-time action is abandoned. It is understood as a permanent competence that should be developed in all areas of the company's functioning (Dutta, Bhardwaj, Mahida, 2024).

In the literature on the subject, it was emphasized that the concept of functioning of agile organizations puts special emphasis on people and their competencies. Employees in such structures are treated as a key resource. His commitment and skills are the foundation of adaptability and the ability to implement change (Kocot, Kwasek, Radowicki, Gontarek, Oleksiejuk, 2025). Agile organizations support competency development. In addition, they promote collaboration and open communication, as well as build an organizational culture based on trust and accountability (Zaccaro, Hiller, Klimoski, 2024; Klimoski, 2023). Decentralization of decision-making processes is also becoming an important element. This allows teams to independently respond to emerging challenges and take actions adequate to the current situation (Fischer, Charef, 2021; Gelec, Dogru, 2024). This approach fosters innovation. In addition, it reduces the time it takes to implement solutions. And this remains particularly important in the context of increasing competitiveness and the speed of change in the market environment (Ruhana, 2025).

The concept of organizational agility is also reflected in the use of modern information and communication technologies that support decision-making processes, facilitate knowledge management and enable more efficient internal and external communication (Bouguerra, Gölgeci, Gligor, Tatoglu, 2021). Thanks to digital tools, it is possible to monitor activities on an ongoing basis, analyze data and adapt strategies to current needs and conditions (Korpivaara, Tuunanen, Seppänen, 2021). Agile organizations are seen as dynamic structures. They combine flexibility with the ability to plan for the long term, creating a balance between quick response and strategic orientation. This concept fits into the broader current of management of modern enterprises, in which the ability to continuously learn and adapt becomes a priority as a condition for sustainable success (Holbeche, 2023).

1.2. The role of digital competences in agile organizations

Modern organizations operating in an agile model are increasingly basing their effectiveness on well-developed digital competencies of employees (Bańkowski, Boiko, Witkowski, 2024; Štaka, Vuković, Vujović, 2022). In a business environment where technology permeates almost every area of the company's operations, the ability to efficiently use digital tools becomes a prerequisite for smooth adaptation to changes and the implementation of new solutions. The ability to process and interpret data, use IT systems or use communication platforms means that organizations can respond to market needs faster. They are also able to adapt their strategies more efficiently to new challenges (Huu, 2023; Korzyński, Mazurek, Krzypkowska, Kurasiński, 2023).

Digital competences also play an important role in building a work culture, based on knowledge sharing and team flexibility. Thanks to them, it becomes possible to create a space where communication runs smoothly, and decisions can be made based on current information. In the structure of agile organizations, functioning in short decision-making cycles, digital competencies support the processes of iterative change implementation. Besides, they mitigate the risk arising from uncertainty (Vuorikari, Kluzer, Punie, 2022; Mehrvarz, Heidari, Farrokhnia, Noroozi, 2021). Their importance goes far beyond technical skills. They can therefore be considered as part of an organizational culture in which technology supports creativity, co-responsibility and continuous development (Foadi, Varghese, 2022; Juhász, Kálmán, Tóth, Horváth, 2022).

The role of digital competences is also evident in the context of globalization and the growing role of distributed teams. Thanks to the efficient use of digital tools, it becomes possible to maintain smooth cooperation in projects implemented in different parts of the world and to adapt activities to dynamically changing conditions on an ongoing basis. In this way, digital competences contribute to broadening the horizons of organizations, strengthening their ability to innovate. They also make it possible to build a competitive advantage on an international scale (Heponiemi et al., 2022).

1.3. Motivating factors for improving digital competences

The motivation to improve digital competences in agile organizations can be shaped by many different factors. They relate to both the individual and professional spheres. An important element is material factors, which are naturally related to employees' expectations regarding remuneration, additional benefits or improvement of economic status (Bolek, Romanová, 2023; Barboutidis, Stiakakis, 2023). The prospect of obtaining measurable financial benefits is a strong incentive to invest time and effort in digital development. This is especially evident in an environment where technology is the basis of daily work and conditions the possibility of participating in more advanced projects (Montilla, Rodriguez, Aliazas, Gimpaya, 2023).

Independence is also an extremely important area, closely related to the sense of agency and the ability to make independent decisions in the context of the work performed. Digital competences increase the scope of this autonomy. This is because they allow individuals to complete tasks faster and more efficiently, without having to rely excessively on the support of others (Díaz-Noguera, Hervás-Gómez, De la Calle-Cabrera, López-Meneses, 2022). The same dimension includes the professional situation, which includes both job security and the possibility of promotion or participation in innovative projects. The increase in digital competences translates directly into the attractiveness of employees on the labor market. Ultimately, this makes this factor one of the most important determinants of skill development decisions (Antonietti, Cattaneo, Amenduni, 2022; Oberländer Bipp, 2022).

The motivation to learn new technologies is also related to the material and life situation of individuals. Stable living conditions are conducive to investing in development. On the other hand, an uncertain situation may limit the willingness to undertake additional educational activities (Zabolotska, Zhyliak, Hevchuk, Petrenko, Alieko, 2021). An important source of motivation turns out to be the prospect of development. It is understood as an opportunity to expand knowledge and acquire new competencies in the long term, which translate into broader career opportunities (Zhao, Sánchez Gómez, Pinto Llorente, Zhao, 2021). Social factors, such as belonging to a group or a sense of identification with an organization, are formed in a slightly different way. Although they are not the main determinant, under certain conditions they can strengthen the readiness to participate in training processes. This is especially evident when the development of digital competences is treated as part of a common goal of the team (García-Vandewalle García, García-Carmona, Trujillo Torres, Moya Fernández, 2023). The picture is complemented by the desire to prove oneself. It expresses the desire to confirm one's own capabilities and face challenges that require new qualifications. This type of intrinsic motivation makes the process of improving competences a necessity resulting from the labor market, but above all a way to build one's own professional identity and sense of satisfaction (Beardsley, Albó, Aragón, Hernández-Leo, 2021).

2. Methods

The aim of the research was to determine the factors motivating employees to improve IT competencies in organizations operating in the agile model and to determine which of them play a key role in the process of digital development. A research hypothesis was adopted assuming that the strongest motivators for investing in the development of IT skills are developmental, professional and material factors, and their interconnections create a coherent motivational system conducive to the development of digital competences. In this context, research questions were posed about which motivational factors employees indicate as the most important in the process of improving IT competencies. What is their mutual significance compared to social factors and how are these motivators related to each other in the perception of respondents? In order to verify the hypothesis, a research method was used in the form of a survey, conducted in 2025 on a sample of 525 respondents. This allowed the collection of a wide range of empirical material. In addition, in order to assess the strength and direction of the relationship between individual motivational factors and to determine which of them form the systems most important for employee motivation in the area of improving digital competences, Pearson correlation coefficients were determined.

The empirical research was carried out in 2025 using a diagnostic survey method. A total of 525 valid observations were collected from respondents representing various types of organizations operating in an agile model. The survey was conducted online between March and May 2025, which ensured access to a geographically diverse sample of participants. The selection criteria included employment in organizations declaring the use of agile management practices and involvement in processes requiring digital competences. The collected material was quantitative in nature, although the questionnaire also contained open-ended questions that allowed for a qualitative extension of the results. To ensure the reliability of the data, the survey tool was pre-tested on a pilot group, and the internal consistency of the scales was verified using Cronbach's alpha coefficients.

In the course of the research, sociodemographic data were obtained to characterize a research sample of 525 people. In terms of gender, women dominated, accounting for 301 people, which constituted 57.3% of all respondents, while men accounted for 224 people, or 42.7% of the surveyed population. Analysing the age structure, the largest group was made up of respondents aged 21-30, who constituted 289 people, which corresponded to 55.0% of the sample. Another group was made up of people under 20 years of age – 151 respondents, or 28.8%. There were 46 people aged 31-40, which was 8.8%, and those aged 41-50 – 32 people, or 6.1%. The least numerous category were people over 50 years of age, who were 7, which corresponded to 1.3% of the total number of respondents.

Taking into account the place of residence, most respondents came from large cities with more than 200 thousand inhabitants – 285 people, which constituted 54.3% of the sample. Subsequent categories included rural residents – 93 people, or 17.7%, cities with up to 20,000 inhabitants – 61 people, which accounted for 11.6%, cities with 21,000 to 50,000 inhabitants – 47 people, or 9.0%, and medium-sized cities with 51,000 to 200,000 inhabitants – 39 people, which corresponded to 7.4% of the total.

In terms of financial situation, people describing it as good prevailed – 273 respondents, i.e. 52.0%. The next group consisted of people indicating an average level – 166 people, which constituted 31.6%. A very good financial situation was declared by 74 people, i.e. 14.1% of the sample, while a bad financial situation was indicated by 12 respondents, which constituted 2.3%.

In terms of professional activity, the largest group were permanently employed employees – 309 people, i.e. 58.9% of the sample. Another group consisted of casual workers – 98 respondents, which constituted 18.7%. 76 people, or 14.5%, remained unemployed. The sample also included people running their own business – 26 respondents, which corresponded to 5.0%, and people combining permanent work with running a business – 13 people, i.e. 2.5%. The smallest group consisted of people running a farm – 3 respondents, which constituted 0.6% of the sample.

3. Results

In the course of the research, efforts were made to identify the factors motivating to improve IT competencies in agile organizations. Figure 1 presents the distribution of respondents' responses.

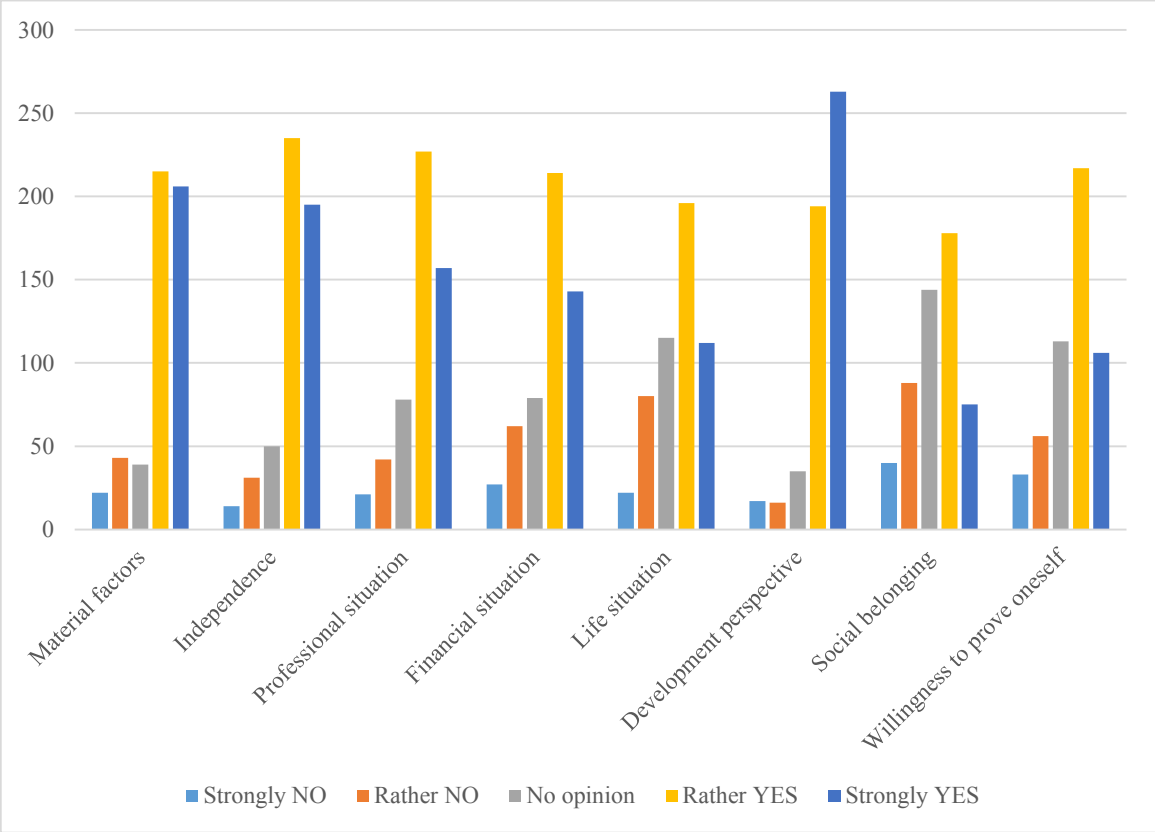


Figure 1. Factors motivating to improve digital competences.

Source: Own study.

In the case of material factors, 22 people (4.2%) declared a strongly negative attitude, 43 (8.2%) rather negative, 39 (7.4%) had no opinion, while 215 (41.0%) assessed it rather positively, and 206 (39.2%) strongly positive. With regard to independence, 14 respondents (2.7%) indicated a strongly negative answer, 31 (5.9%) rather negative, 50 (9.5%) remained neutral, while 235 (44.8%) chose a rather positive option and 195 (37.1%) a strongly positive one. The professional situation was assessed strongly negatively by 21 people (4.0%), rather negatively by 42 (8.0%), neutrally by 78 (14.9%), while 227 (43.2%) indicated a rather positive answer, and 157 (29.9%) a strongly positive answer.

In the case of the financial situation, 27 people (5.1%) expressed a strongly negative opinion, 62 (11.8%) rather negative, 79 (15.0%) remained unopinionated, 214 (40.8%) considered it rather positive, and 144 (27.3%) considered it to be strongly positive. Analysing their life situation, 22 respondents (4.2%) indicated a decidedly negative answer, 80 (15.2%) rather negative, 115 (21.9%) did not take a position, 196 (37.3%) considered it rather positive,

and 113 (21.4%) considered it to be decidedly positive. The prospect of development was assessed negatively by 17 people (3.2%) definitely and 16 (3.0%) rather, 35 respondents (6.7%) did not have an opinion, while 194 (37.0%) indicated a rather positive answer, and as many as 263 (50.1%) strongly positive. Social affiliation received strongly negative indications from 40 people (7.6%), rather negative from 88 (16.7%), neutral from 144 (27.3%), rather positive from 178 (33.9%) and 76 (14.4%) definitely positive.

On the other hand, the desire to test themselves was indicated by 33 people (6.3%) who were strongly negative, 56 (10.7%) were rather negative, 113 (21.5%) were neutral, as well as 217 (41.3%) were rather positive and 106 (20.2%) were definitely positive.

Table 1.
Correlation table

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	1							
2	0,99	1						
3	0,94	0,98	1					
4	0,93	0,96	0,99	1				
5	0,75	0,82	0,91	0,93	1			
6	0,96	0,93	0,85	0,82	0,61	1		
7	0,41	0,52	0,67	0,70	0,90	0,24	1	
8	0,76	0,83	0,92	0,93	0,97	0,61	0,88	1

Source: Own study.

The analysis of the results presented in Figure 1 was deepened by calculating the Pearson linear correlation coefficients (see Table 1). This list allows for the assessment of the strength and direction of the relationship between individual factors motivating to improve IT competencies in agile organizations. The coefficient values indicate very strong positive relationships between most variables. The highest correlations occurred between professional situation and material situation (r = 0.99), as well as between life situation and the desire to prove oneself (r = 0.97). This confirms that these areas are closely related in the perception of the subjects. Strong correlations were also noted between material factors and development prospects (r = 0.96), as well as between independence and professional situation (r = 0.98).

At the same time, the presented analysis indicates the existence of weaker links in relation to social affiliation, whose relationships with other factors, especially with the prospect of development (r = 0.24) and material factors (r = 0.41), turned out to be significantly lower. This may mean that this aspect functions in a slightly different way than other motivators. And also the fact that it is not so clearly linked to material or professional conditions. It can be concluded that the overall picture presented in Table 1 is consistent with the distribution of responses seen in Figure 1, where most factors obtained high percentages of positive responses, which in turn translates into the predominance of positive and strong correlations between them.

4. Discussion

The presented results of empirical research allow the conclusion that the motivation to improve IT competencies in agile organizations is based mainly on the strong influence of professional, developmental and material factors. The analysis of the distribution of respondents' responses presented in Figure 1 indicated that factors such as development prospects, independence, professional situation, or material factors were assessed positively in the vast majority of cases. High percentages in the categories "rather yes" and "definitely yes" prove that the respondents equate the development of their IT competences with the possibility of achieving benefits both in the personal and professional dimension. Especially the development prospect received by far the highest positive indications, which highlights that developmental factors are the strongest motivational driver in the aspect of improving digital skills.

The obtained results remain in close relation to the previous findings presented in the theoretical section and confirm the importance of developmental, professional, and material factors in the process of enhancing digital competences. Similar relationships were indicated in the study by Lee, Lee and Hwang (2015), which demonstrated that autonomy and a sense of competence play a key role in the acceptance of technology in the workplace. Convergent conclusions were also presented by Jo and Hong (2022), who emphasized the role of organizational support in shaping innovative employee behaviors. In light of the obtained results, it can be stated that the findings not only confirm previous research but also deepen it by revealing the interdependencies between material, developmental, and professional factors, which jointly create a coherent motivational system. In this way, the empirical section provides a practical complement to the theoretical considerations and strengthens the link between the literature review and the analyzed constructs and measurement variables.

These observations are consistent with other studies. The great importance of the perspective of development and professional stability corresponds to the findings of Lee, Lee and Hwang (2015), who showed that autonomy and competence play an important role in the acceptance and use of technology at work. Convergent conclusions can also be found in research on learning agility, which highlights the importance of organizational support in the development process and innovative employee behaviors (Jo, Hong, 2022). In addition, studies on digital competences at work indicate that autonomy, fairness and support are key factors fostering both well-being and digital growth (Audrin, Audrin, Salamin, 2024). Similar directions are also emphasized in advisory reports, which stress the need to combine competence development with remuneration systems and clearly defined career paths (McKinsey & Company, 2023). Research on motivational factors in agile organizations confirms that work flexibility, development, and transparency of promotion are key determinants of engagement, which is consistent with the results obtained (Kwasek et al., 2024).

The above observations were confirmed by the analysis of Pearson's correlation coefficients. The correlation shown in Table 1 demonstrated very strong positive relationships between most variables. Such a high convergence of indications proves that professional, material, and life factors co-create a coherent motivational system. Correlations at the level of 0.99 or 0.97 show that the improvement of the professional and material situation is closely related to the sense of development and the desire to prove oneself. This means that in the perception of employees, investing in IT competences can be considered a determinant of building stability, prestige, and professional security.

At the same time, attention should be paid to the weaker relationships recorded in the case of social affiliation, whose correlation coefficients with other factors were significantly lower. This result suggests that motivations related to the feeling of being part of a social or organizational group cannot be considered as a key determinant in the process of improving IT competences. It can be assumed that in this area, individual benefit rather than social affiliation is more important. This indicates the dominance of pragmatic and individual motivations over collective motivations.

A holistic picture of the research results therefore indicates that in the context of agile organizations, material, professional, and developmental factors are of key importance in the development of IT competencies, which mutually reinforce each other and create a coherent system of connections. Employees overwhelmingly equate improving digital skills with improving their professional situation, financial stability, and career opportunities. In this way, the motivation for learning and technological development fits into the broad context of the individual's functioning in the work environment and is based on expectations related to safety, promotion, and self-fulfilment.

In light of the results obtained, it is recommended that organizations operating in the agile model focus their activities on creating such working conditions that strengthen material, professional, and developmental factors to the greatest extent. It is also important to provide opportunities for systematic development through access to training, mentoring, and projects enabling the acquisition of new skills, as the prospect of development has proven to be the strongest motivating factor. At the same time, it is advisable to build professional and material stability, among other things, through transparent remuneration systems, bonus programs related to the development of digital competences, or the creation of career paths. The latter clearly reflect the opportunities for promotion and development in the organization. To a lesser extent, attention should be paid to social motivators, as their importance in the context of the development of IT competences is limited. Nevertheless, they should not be completely omitted but rather treated as a complement to activities aimed at individual development. Such an approach will allow organizations to engage employees more effectively, increase their level of competence, and build a competitive advantage based on knowledge and technological skills.

5. Conclusions

The conducted research allowed for the identification of the most important motivational factors influencing the development of IT competences in agile organizations. Developmental, professional, and material factors proved to be the strongest motivators, creating a coherent system of interdependencies that fosters digital growth. Social affiliation, on the other hand, played a significantly weaker role, which suggests that individual and pragmatic incentives prevail over collective ones. In this respect, the adopted research hypothesis was confirmed.

The research was not free from limitations. Its cross-sectional nature made it possible to capture relationships only at a given moment in time, without the possibility of observing long-term changes. The study was based on self-declared responses, which entails the risk of subjectivity and the influence of personal and professional experiences on the provided answers. Moreover, sectoral differences and the specificity of professional roles were not included, although they may significantly shape motivational structures. These limitations should be taken into account when generalizing the obtained results.

Despite these constraints, the research contributed new knowledge by empirically demonstrating the interrelationships between developmental, professional, and material factors, which jointly form a coherent motivational system. The findings provide both theoretical and practical implications. From a theoretical perspective, the study complements the existing body of knowledge on digital competences in agile organizations by highlighting the motivational mechanisms that underlie competence development. From a practical perspective, the results indicate the need to create organizational conditions that combine professional stability, transparent career paths, remuneration systems, and continuous access to development opportunities.

Future research should consider longitudinal studies to identify how motivational structures evolve over time. It is also advisable to include sectoral analyses and comparative studies across different organizational contexts, which would make it possible to capture the diversity of motivational systems and their determinants in a broader perspective. Future research should also include qualitative analyses, such as interviews or focus groups, which would make it possible to better understand the mechanisms behind the relatively weak role of social affiliation as a motivational factor. Such an approach could reveal contextual and cultural determinants that are not fully captured by quantitative methods and would provide a deeper explanation of why this factor differs from the others.

Future research could also examine the moderating role of financial situation in shaping motivational structures. Applying regression models would allow testing whether economic status significantly alters the hierarchy of motivators and whether employees in different financial conditions prioritize developmental, material, or professional factors differently.

In addition, further studies should take into account organizational culture aspects, such as leadership style, communication practices, and team collaboration. Including these dimensions would provide a fuller picture of how agile organizations can support digital competence development and would extend the analysis beyond individual-level motivators.

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IMPLEMENTATION OF WORK EFFECTIVENESS MONITORING SYSTEMS IN PUBLIC ADMINISTRATION: OPPORTUNITIES AND CHALLENGES

Marek MAGDOŃ[1], Seweryn TCHÓRZEWSKI[2*]

[1] University of Economics in Katowice; marek.magdon@ue.katowice.pl, ORCID: 0000-0003-3517-4329
[2] Silesian University of Technology; stchorzewski@polsl.pl, ORCID: 0000-0002-7039-1276
* Correspondence author

Purpose: The aim of the work is to present a practical example of the process of defining and implementing the guidelines of monitoring work effectiveness in a selected public administration entity.
Design/methodology/approach: The analyzed materials include the developed work models in the selected organization (case study), notes from meetings of the team supervising the implementation, also post-implementation comments collected during personal observations (participant observation) and discussions with people directly carrying out the work (in-depth interviews).
Findings: The publication presents a model that was developed for organizing the process of collecting information about the work performed by employees of the selected entity. The model was analyzed and critical elements that should be improved were identified.
Practical implications: The development process and critical analysis of the obtained results for a model for implementing the guidelines of monitoring work effectiveness in selected organizational units of a large public administration entity are presented. Given the intended implementation of the solution across the entire entity, the model was subjected to critical analysis (good and bad practices were inventoried during the work).
Originality/value: The presented experiences are shown from the perspective of the team preparing and implementing the developed solution, demonstrating a methodical approach to the entire process and the need for individualized treatment of different areas of the organization. The authors believe that the developed solution, despite its limitations resulting from its location within a specific organization, can be widely used in implementing similar systems in other entities, both in Poland and abroad.
Keywords: work effectiveness, implementation of management procedures, work productivity, management systems.
Category of the paper: Research paper, Case study.

1. Introduction

Every human action is viewed through the prism of its effectiveness. It's no surprise, then, that effectiveness is a crucial management issue for any organization, impacting all aspects of its operations, including achieving defined goals, effective resource utilization, organizational image, and employee motivation. Effectiveness is a measure of the degree to which appropriate goals are set and achieved. In other words, it informs how well assigned tasks are performed (Stoner et al., 1999).

An organization's success or failure depends largely on the level of individual employee effectiveness. Organizations use employee effectiveness information in various aspects of their operations, such as strategy, administration, communication, and development. Knowledge about employee effectiveness enables them to provide constructive feedback, plan development activities, reorganize employee work, and make decisions about resource allocation (Grobelny, 2023; Sauermann, 2023).

In an era of advancing digitalization and increasing pressure on the efficiency and accountability of public institutions, monitoring work effectiveness is gaining particular importance. Despite being widely studied in the private sector (e.g., Franco-Santos et al., 2012; Kalischko, Riedl, 2024; Vuong, Nguyen, 2022), this topic still lacks in-depth research that accounts for the specific characteristics of public administration.

This article presents experiences collected during the implementation of a systemic approach to collecting and utilizing information about tasks performed by employees of selected organizational units of a public administration entity in Poland. A dedicated implementation model for selected areas is presented for this entity, which could be implemented across the entire organization in the future. Based on the collected experience, critical conclusions are drawn that allow for the improvement of the proposed model.

The originality of this paper lies in the combination of a theoretical perspective with practical experience gained from implementing a work effectiveness monitoring system in a specific public administration entity. The proposed model, based on a real case study, may serve as a reference point for other institutions seeking effective tools to enhance performance. In this way, the article contributes to the ongoing discourse on modern public management, providing both theoretical insights and practical value.

2. Effectiveness: the concept and importance of measurement

Effectiveness is one of the main subjects of interest in both management sciences and economics (Samuelson, Nordhaus, 1999; Stoner et al., 1999; Ziębicki, 2010; Szymańska, 2010; Zbierowski, 2017). According to P. Drucker (2006, p. 167) effectiveness has become „[…] crucial to a man's self-development; to organization development; and to the fulfilment and viability of modern society". It is a measurable, gradable and relative category, used to make assessments and value judgments (Malik, 2004). Depending on the approach adopted, both the criteria and the measures used for its assessment will differ – the static approach is based on the principle of rational management, while in the dynamic approach, the category of scarcity plays a key role. The essence of the static approach to effectiveness is the degree of achieving the assumed goals and improving performance, while the point of the dynamic approach is the ability to acquire and properly utilize resources. In the literature, the static approach is also referred to as the purpose-oriented, while the dynamic approach is referred to as the systemic approach (Malik, 2004).

In the static approach, the evaluation criteria include effectiveness (maximizing the compliance of achieved results with established goals), management efficiency, understood as profitability (maximizing the difference between achieved results and incurred costs), and cost-efficiency (optimizing the relationship between results and costs). Evaluation measures, in turn, may include: added value, profit, return on investment (ROI) and the degree of goal achievement. In the case of dynamic effectiveness, the evaluation criteria include the ability to acquire optimal amounts of resources to maximize the organization's market position and the performance of the organization itself. A measure of effectiveness understood in this way may be the maximization of income generated in relation to available resources (Malik, 2004; Kowal, 2013; Becla et al., 2024).

In the case of a public administration entity, the Act of 27 August 2009 on public finances (consolidated text published in Journal of Laws of 2024, item 1530) obliges to measure effectiveness at the level of the organization as a whole, defining management control and indicating its objectives (Article 68) (Sakowicz et al., 2014). However, the effectiveness analysis may concern various organizational levels, such as (Skowron-Mielnik, 2009):

– individual employee (individual effectiveness),
– team of employees (group effectiveness),
– separate organizational units (department, division, unit),
– the organization and its employees as a whole.

The further the work effect is from its direct performer, the more difficult it is to indicate specific reasons for the improvement or deterioration of results and to justify the decision to increase or decrease the expenditure incurred on these effects (Skowron-Mielnik, 2009).

Management science generally emphasizes the importance of performance measurement and analysis – effective management requires accurate performance measurement, because only then can managers make appropriate decisions and assess the organization's progress. Without monitoring and measurement, how could managers gain knowledge about how organizational units and the teams under their control are performing?

It turns out that many organizations don't measure their results on an ongoing basis and are therefore unable to manage their performance. Therefore, effectiveness measurement seems crucial to improving productivity and ultimately ensuring organizational sustainability (Sookdeo, 2019). Effectiveness measurement involves collecting data on the performance level of a specific unit over a specific period of time and assigning a numerical value to that level. This assignment is performed on a specific scale, and the numerical data is collected using indicators – an indicator is a key element of the measurement process (Grobelny, 2023). Work effectiveness is a complex process that cannot be based only on one indicator, therefore the use of various methods and tools allows for a more complete picture of effectiveness, taking into account both quantitative and qualitative aspects of work (Evans, 2023). Monitoring and assessing the effectiveness of work performed is a standard management activity whose origins date back to the pre-industrial era – back then it was carried out through direct "observation from behind" (Woźniak, 2021).

Measuring work effectiveness can bring tangible benefits, including (Mierzenie wydajności pracowników…, 2024):

- increasing operational effectiveness – monitoring effectiveness enables the detection of areas requiring improvement, which makes it possible to optimize operational processes, which in turn leads to an improvement in the overall effectiveness of the organization,
- better work planning – measuring effectiveness helps in effective human resources management by matching the number of employees to the current needs related to the implementation of tasks, provides specific data for effective work planning depending on changing conditions,
- quick response to changes in processes – regular monitoring allows management to quickly respond to emerging problems and make appropriate changes in the distribution of tasks between teams to ensure process continuity and timely completion of tasks,
- optimization of financial resources – measuring effectiveness allows us to identify areas where financial resources are used inefficiently, optimizing these resources leads to improving the way funds are spent,

- motivating employees – knowing that their performance is monitored encourages employees to be more engaged and focused,
- individual employee development – measuring effectiveness allows to detect strengths and areas requiring improvement in individual employees, on this basis, it is possible to adapt training programs to their individual development needs,
- fair employee evaluation – regular performance monitoring provides reliable and objective information that can be taken into account when assessing an employee; recorded data, based on specific indicators, can influence the bonus process, which gives employees a sense of fairness and influence on results, and consequently increases their motivation,
- development of organizational culture – regular evaluation of employee performance contributes to the creation of a positive organizational culture in which achievements are appreciated and encountered difficulties are treated as opportunities for development and improvement,
- replicating good practices – comparing performance data across teams or locations enables the identification of effective practices that can be implemented in other parts of the organization, fully utilizing the potential of all employees,
- identification of potential leaders – analysis of the results helps to detect people with high potential to fulfill leadership roles, constituting a valuable source of information when planning staff development, professional career and succession.

A. Gębczyńska and R. Brajer-Marczak (2020), based on their literature review, indicate that publications in the field of efficiency management in public administration focus on three areas: methods of measuring efficiency, the increased use of information derived from efficiency (including performance) measurement, and the impact of performance management on achieved results. Other authors (Hammerschmid, Löffler, 2015; Kohtamäki, Olsson, 2018) address the issue of implementing an effectiveness management system not at the level of a single institution, but at the national level – across the entire sector, on a macro scale. They present legislative solutions, the size of the public sector, the scale of public spending, and similar factors. However, the literature review revealed no studies addressing a model for implementing work monitoring guidelines in a public administration entity, nor the associated difficulties, opportunities, and challenges. This article aims to fill that research gap.

3. Methods

This article presents the results of research collected during the implementation of effectiveness measurement guidelines in a selected public administration entity. The organization's developed principles and reference model were assessed, ultimately serving to systematically implement the adopted solution across the organization. The research process included the following stages:

1. Describing the implementation model for work effectiveness assessment guidelines implemented in the selected entity (case study).
2. Testing the correctness of implementing this model in practical application with a critical analysis of the obtained results conducted in the form of personal observation (participant observation) and interviews with people implementing the adopted solution (IDI).
3. Proposing modifications to the target/reference solution.

During the research, the following were used: internal documentation of the organization, such as organizational regulations, implementation documentation, and results of interviews with the entity's employees.

3.1. Premises for introducing an effectiveness monitoring system

The analyzed public administration entity carries out tasks aimed at providing citizens of a selected area of Poland with access to a range of support, control, and administrative decision-making services. Over the past ten years, the growing number of responsibilities and the increasing amount of funds distributed by the entity have led to its expansion. The number of employees and the size of the structure have led to a noticeable increase in the inertia of intra-organizational processes and a lack of clarity regarding the status of ongoing tasks. The number of existing departments has increased, contributing to the typical "silo-ing" of the organization by carrying out their specialized tasks. At the same time, the number of decision-making levels increased, hindering internal communication and monitoring the effects and outcomes of assigned tasks. Consequently, the decision was made to implement a solution that would enable effective management of the organization, where "effective" meant providing citizens with the best possible results, for example, quick access to information. Considering the factors mentioned above, the following requirements and goals were defined for the system being developed:

1. Improving the monitoring of the pace and degree of achievement for the goals set for entity individual organizational units.
2. Support for the management process of individual organizational units of the entity – based on numerical data, it will be possible to draw conclusions and take actions in the context of planning, organizing, managing human resources and controlling the implementation of assigned tasks.
3. Assessment of work effectiveness in individual organizational units of the entity – indicators enabling measurement are to be introduced (minimizing the subjectivity of the assessment).
4. Support for the decision-making process in relation to the allocation of human resources, including decisions on the number and type of tasks delegated to individual employees – management decisions will be made on the basis of indicators/numerical values.
5. Support for the decision-making process in relation to the bonus system – decisions will be made on the basis of numerical, measurable and verifiable indicators/values.

Due to the previously mentioned growth of the organization, it was assumed that, in principle, the study of the effectiveness of processes implemented in the organization should take into account three levels:

1. Employee level – this level measures the work performed by a specific employee on a specific working day and time. This is not computer tracking, but rather a conscious employee service activity – reporting will involve recording the types of tasks performed by a given organizational unit and recording the time it takes to complete them.

   Due to the nature of the work, continuous time reporting down to the minute was not recommended. Although this approach is highly accurate and allows for highly precise verification of employee work time, it comes with administrative costs, including the need to dedicate time to "switching" between tasks and often overly detailed planning of the workday. As a result, in extreme cases, effectiveness can decrease. Therefore, it was proposed that employee time reporting should include some simplifications and rounding. For the pilot study period, it was agreed that the minimum unit would be 15 minutes, with employees able to report their time in full at the end of the day.
2. Team manager level – its task will be to analyze data entered by employees. This will allow to generate summary tables and/or charts indicating how much time was used on specific kind of tasks and how much time team members spent achieving particular work results. This layer will display results in the form of calculated performance indicators, including those compared to previous periods and defined reference values. Access to the data will be limited to employees reporting to a given team manager who has performed similar tasks.

3. Director level – it will be possible to obtain and observe exactly the same information available to a team manager, but without limiting it to employees of a specific team, but for the entire department, divided into teams. Importantly, this level will define reference values for indicators and allow for the addition of new tasks, i.e., expanding the dictionary of existing tasks for the employee to choose from. Collecting and inventorying this data over a longer period (over three months) will allow for the definition/construction of reference values.

   In fact, it is the department directors who will be the main recipients of the entire solution, because based on the inventoried data it will be possible to take actions in the field of assigning tasks, setting bonuses, or in extreme cases, making changes within the organizational structure of the department.

Typical indicators used to analyze recorded work time are presented in detail in the appendix to this publication.

3.2. Initial implementation model of the effectiveness monitoring system

The significant diversity in the content of the monitored activities indicated the need to implement a solution that would be simple and universal enough to be implemented, if not in all, then at least in most of the existing departments. The identified needs were transformed into a plan for implementing changes within the organization (see Figure 1). They were proposed to be implemented in the following order:

1. Developing guidelines for measuring work effectiveness for both quantitative and process-based tasks. Needs and challenges were identified, and existing administrative processes were analyzed, including existing procedures, regulations, organizational structure, and management and organizational solutions in selected organizational units.
2. Selecting three departments to test the proposed solution. This allowed for data collection and information on the existing methods for measuring the effectiveness of administrative processes and human resources management in selected organizational units.
3. Implementation of the proposed guidelines for selected areas, along with the principle of including subsequent areas on a monthly basis, which allowed, based on previously gathered experience, to develop a model adequate to the functioning of the organization, possible to implement in other areas. Evaluation of the collected data for its usefulness and suitability to the specification of selected organizational units.
4. Developing an IT tool that allows for viewing collected data on ongoing tasks. Work on this system was carried out in parallel with the tasks listed in points 2 and 3.
5. Formulating recommendations – based on the identified benefits and limitations, a set of recommendations was developed.

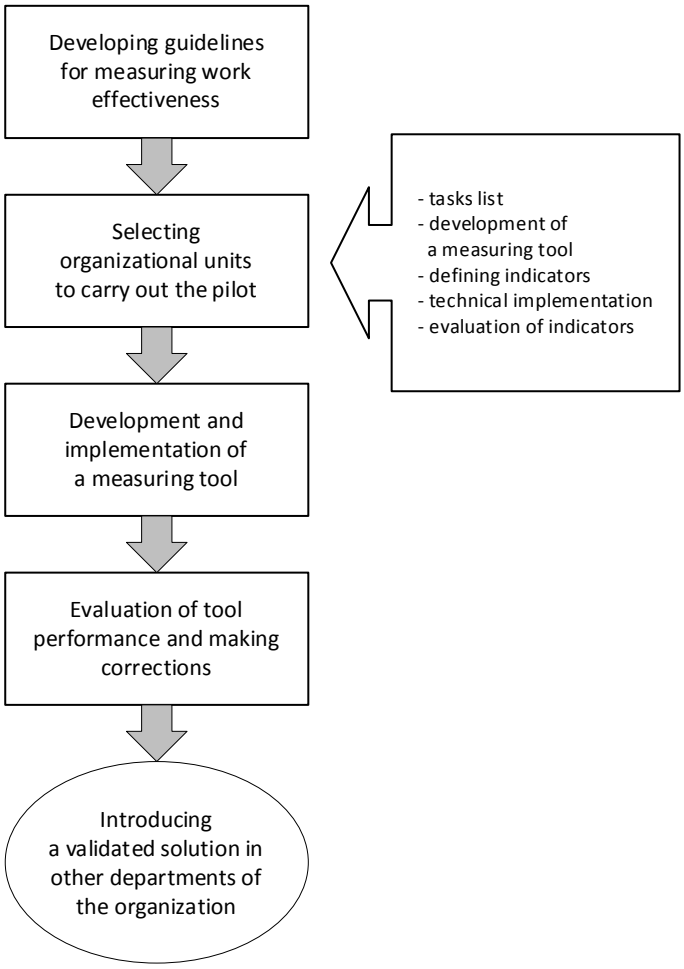


Figure 1. The initial model for implementing work monitoring guidelines in a public administration entity.

Source: authors' own work.

The process of implementing a measurement tool that allows for the assessment of the effectiveness of activities conducted in individual organizational units of a public administration entity using partial indicators will require the following actions:

1. Defining a list of tasks to be performed in individual teams/areas within each department.
2. Developing a department-specific measurement tool.
3. Defining indicators specific to each department.
4. Technical implementation of the measurement tool.
5. Evaluating the achieved indicators and their potential modification, and proposing reference values for subsequent periods.

4. Results

The results of the pilot implementation allowed for the practical confirmation of the possibility of adopting the proposed solution, while taking into account the comments and recommendations for improvement formulated below. Proposed solution functioning scheme is presented on the example of the area related to wages and salaries – one of the indicators presented in the annex (the indicator of the employee's task completion time) was used to analyze the collected data. Next, based on data from one settlement period (e.g. quarter), the target structure of indicators (number, type and structure of individual indicators) used to measure work, as well as the expected reference value allowing for the target measurement of work effects, were to be proposed. Due to the different nature of work in individual areas of each department of the organization and the level of advancement and awareness of employees in relation to performance measurement, it was determined that it is not possible to introduce universal measures for the entire organization – each department requires an individual approach to defining measures. Furthermore, it was proposed that at this stage, attempts to standardize and compare effectiveness not only between entire departments of the organization but also between units within a single department should be abandoned (only when the solution has "solidified" will it be possible to address this issue).

The structure of the form for collecting data by employees (the example uses a measurement tool created in MS Excel) has been adapted to the specific nature of work in the department. Employees completed information regarding, among other things, the type of task performed on a given workday, its start and end time, and the amount of work performed within a given task. A synthetic analysis of the collected data is possible by creating appropriate pivot tables. A summary of sample information useful from the point of view of managing an organizational unit carrying out work in the area of wages and salaries is presented in Table 1. It contains information that allows us to see the amount of specific work performed by each employee of the unit in the analyzed period in relation to the time allocated to these tasks.

Even such a comparison makes noticeable the differences in effectiveness of the same tasks performed by different employees – further calculation and analysis of the indicators will facilitate and speed up the interpretation of the results. For example, the table shows that in the analyzed period employee 2 and employee 4 performed the same task, i.e. "Sick pay - calculation", with employee 2 preparing 100 of these documents in 5.5 hours, and employee 4 preparing 5 documents in 3.58 hours. The indicator of the task completion time by an employee is therefore 3.3 minutes/document for employee 2 and 42.96 minutes/document for employee 4. Such a large discrepancy requires the manager to carry out further, in-depth analysis and explain the reasons for the differences in the obtained results.

Table 1.
An example of an information summary on work input and output for a given period in the area of wages and salaries

Row label	Sum of Working time	Sum of Numbers
Employee 1	**16:54**	**29**
Additional payroll – preparation, printing, circulation	0:54	2
Main payroll	4:00	2
Holiday pay	12:00	25
Employee 2	**8:54**	**111**
Sick pay – payroll	3:24	11
Sick pay – calculation	5:30	100
Employee 3	**9:00**	**151**
Preparing payrolls	8:00	150
Pool – quarterly prizes	1:00	1
Employee 4	**19:05**	**48**
Preparing payrolls	7:30	23
Preparing transfers to the bank accounts of employees, councillors, and to the Tax Office, Social Insurance Institution, State Fund for Rehabilitation of Disabled Persons (PFRON), Employee Capital Plans (PPK)	8:00	20
Sick pay – calculation	3:35	5
Employee 5	**2:00**	**14**
Internal reports	2:00	14

Source: authors' own work.

The collected data can also be presented graphically, for example, in a bar chart. An example of such a presentation, available to department managers (limited to the department) and the department director, is shown in Figure 2. The chart shows which employees spent time on specific tasks on which days. At this stage, the solution allows for ongoing monitoring of work within the organizational unit.

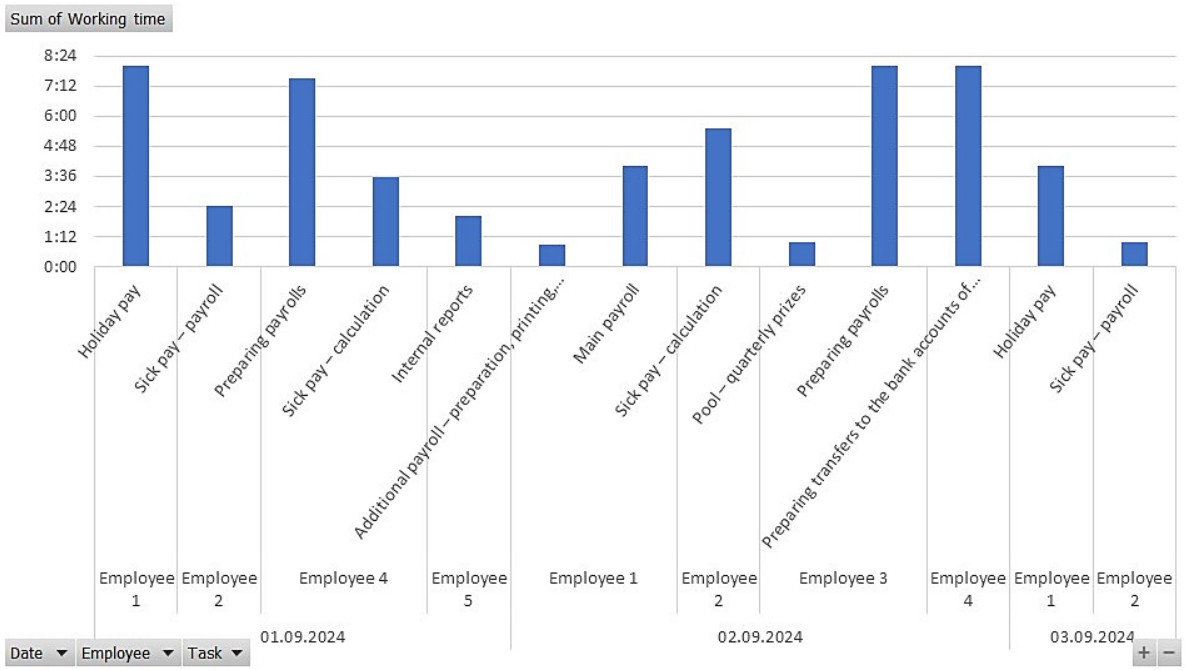


Figure 2. An example of presenting data graphically at the level of a manager and department director.
Source: authors' own work.

The practice of the implementation process has shown that adopting a solution consisting in selecting representative areas of the organization to verify the correctness of the implementation of a new organizational solution brings positive results, although during the implementation process itself, clear limitations were noticed, which include:

1. **Lack of support from the organization's management** for undertaken implementation activities, including, above all, the lack of conviction of department directors to use management methods based on numerical values. As a result of this, and/or directors' reluctance to properly utilize the measurement tool and the resulting data analysis capabilities, the solution may prove to be "dead". It is therefore essential to raise awareness that performance measurement largely serves the directors' actions. Precise definition of results is essential—this cannot be left to "managers' acumen to get things done".
2. **Low level of technical competence among employees**, resulting in errors during the data entry process. During the work, it was observed that using even a simple tool developed in MS Excel can be challenging for employees. Due to difficulties in technically mastering the application, errors occurred relatively frequently, resulting in distorted analysis results.
3. **Low technical competence of management**, making it impossible to generate the summaries and interpret data. When using an MS Excel-based solution, creating a summary of data obtained from individual departments, and then calculating and interpreting indicators, required department managers and department directors to have some MS Excel skills, which they unfortunately did not possess.
4. **Employee resistance** to monitor their tasks. Employees often viewed performance measurement as a threat to their employment stability—a typical case of the "breathe down employee's neck" syndrome. A lack of understanding of the concept of performance measurement led to criticism of the solution and even attempts to block its implementation (including through trade union activity). Consequently, a training cycle was proposed to clarify the goals and guidelines of implementation.
5. **Underestimating the time** required to properly develop appropriate/adequate implementation measures with department employees, as well as the time required to check the correctness of the adopted task granulation**.**

Additionally, lower-ranking issues were also inventoried, but still worth noting:

– the need to correctly identify activities/tasks that should be monitored – in discussions between managers and teams!,
– the need to place greater emphasis on measuring the work and results of a team of employees rather than measuring the work of individual employees performing the same task,

– multi-level task division (task-subtasks); a single-level division will not allow for a holistic, broad view of the area's activities. By introducing a large number of tasks in a drop-down list for the employee to choose from, a single-level division does not allow for proper analysis of processes and tasks with longer execution times.

To sum up, consciously limiting the scope of the implementation to test areas allowed to identify places that require special attention and support when the system is launched across the entire entity.

5. Discussion

Drawing on lessons learned during early testing phase of the model, it was noted that the structure of indicators and reference values should be defined individually for each department. It was also recommended that comparisons of performance between departments and/or their units be considered only after the solution has been fully stabilized. These conclusions align with the issues in selecting and using indicators highlighted by J. Grobelny (2023), including the question of measure validity – that is, the extent to which the result obtained using an indicator accurately reflects the employee's performance level, rather than other phenomena or confounding factors.

Based on the experience from the pilot implementation, it can be assumed that all of the above-mentioned implementation stages require a series of training sessions for employees, department managers and directors as this will present the technical aspects of using the tool and emphasize its importance. Furthermore, it is recommended to correlate the obtained indicator values with the organization's existing motivational system and to modify it accordingly, especially since – as noted by B. Skowron-Mielnik (2009) – companies rarely develop their own remuneration systems, most often adapting solutions from other organizations.

Taking into account the occurrences observed during the implementation process and the comments and limitations mentioned earlier in this article, an improved solution implementation model was proposed, supplemented to the form presented in Figure 3.

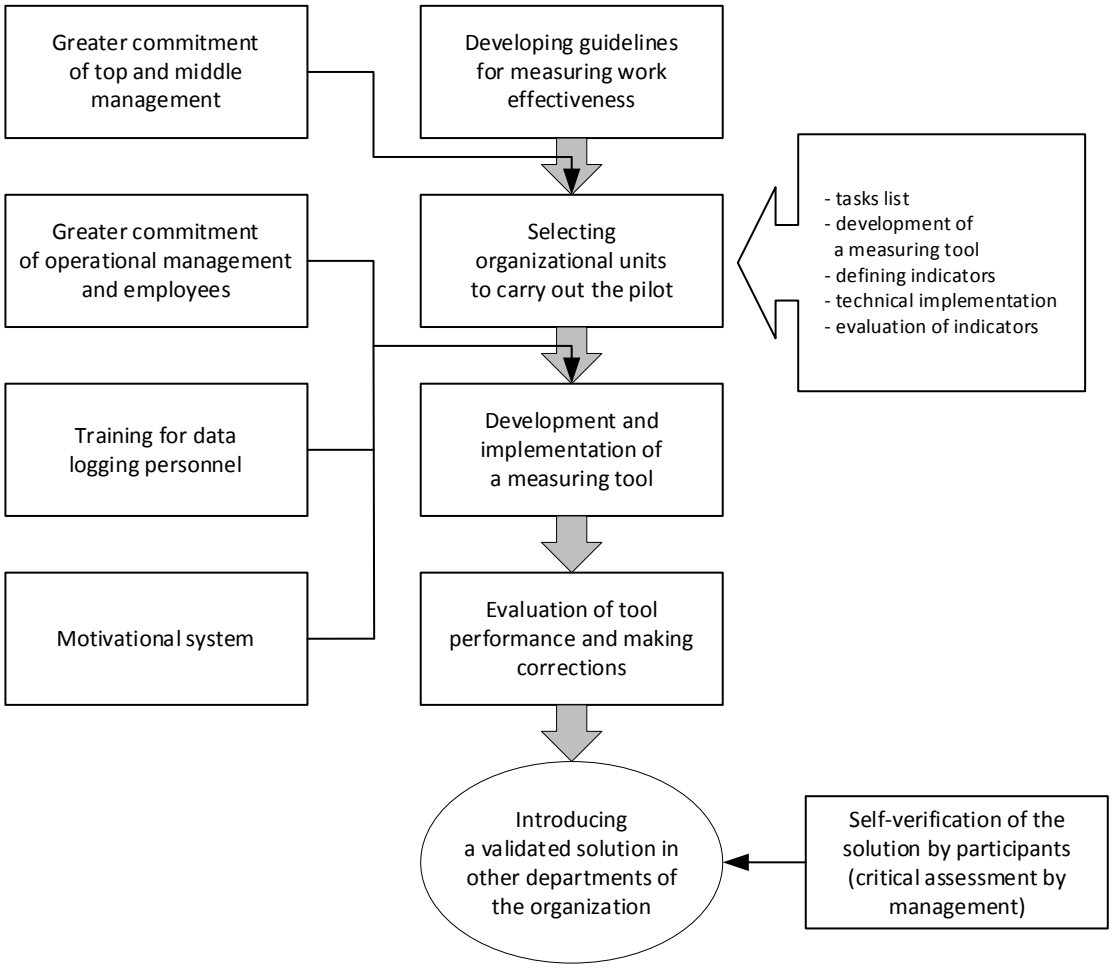


Figure 3. Target model for implementing work monitoring guidelines in a public administration entity. Source: authors' own work.

It's worth noting that IT support is an essential element of the entire process that should be considered. Given the complexity of the activities the entity undertakes, the use of computer software throughout the process is obvious, given that – as J. Woźniak (2021) emphasizes – the development of information and communication technologies has enabled numerous new forms of monitoring, and the emergence of modern tools and observation methods has led to a significant increase in interest among practitioners and researchers in work monitoring. Two basic solutions for the technical implementation of the tool have been proposed:

1. Using the widely used MS Excel program. The employee completes an Excel spreadsheet shared with other department employees, which will be processed manually by the unit head and department director. This solution will require employees to devote time to complete certain amount of data by typing it in. Furthermore, the tool will require work from unit heads and the department director to generate summary reports and indicators (see the limitations mentioned in the previous section).

2. Using dedicated software. The employee will enter the necessary data, but all values will be calculated automatically in the background. Additionally, the interface can be much more user-friendly than MS Excel, reducing the number of potential errors made by employees completing Excel spreadsheets. However, this solution will require financial resources (for buying a license) or executive resources if the application is to be developed in-house.

These conclusions align with B. Evans (2023), who asserts that the effectiveness of measurement depends not only on the implementation of indicators but also on the quality of the tools and their use.

6. Summary

The subject literature emphasizes the importance of measurement and analysis of results, which allows managers to make appropriate decisions and assess progress toward achieving organizational goals. One of the standard management activities is monitoring and assessing work effectiveness, which dates back to the pre-industrial era and is associated with direct observation. It is noted that indicators are a key element of the measurement process. However, because work effectiveness is a complex process, its measurement cannot be based solely on a single indicator.

The aim of this article was to present a practical example of the process of defining and implementing effectiveness monitoring guidelines in a selected public administration entity. This goal was achieved by presenting the experience gained in implementing a systemic approach to collecting and using information about tasks performed by employees of selected organizational units of a public administration entity, as well as presenting a dedicated implementation model for this entity, which could be implemented across the entire organization in the future. Based on the collected experience, critical conclusions were formulated to improve the proposed model, namely:

- support for the organization management, indicating the goals of the implemented solution,
- technical preparation of employees and managers, enabling the correct inventory and processing of information about the tasks being performed,
- proper assessment and identification of those tasks that should be monitored,
- designing a motivational system that takes into account reference values and the achieved values of adopted indicators.

Taking the above considerations into account, the implementation of a work effectiveness monitoring system requires a holistic approach that integrates technical, organizational, and cultural aspects. Only the active involvement of all management levels and employees can ensure lasting and measurable benefits from effectiveness measurement. The proposed model represents a significant step toward improving management processes in public administration and may serve as a benchmark for similar entities seeking to enhance the quality of their operations.

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Appendix

Table 2.
Summary of proposed indicators for the analysis of recorded amounts of working time in the area of wages and salaries

No.	Indicator	Calculation method	Unit of measure	Interpretation
1.	Productivity	$W_P = L_{ZR} / E$	piece/person	L_{ZR} – the number of tasks of a given type completed in a given time period, converted into the number of positions E performing a given type of tasks. - The higher the value of this indicator, the better.
2.	Time taken to complete the task by the employee	$W_{CRZP} = C_P / L_{ZRP}$	minute/piece	C_P – total time spent by an employee on a given type of task in a given time. L_{ZRP} – number of tasks of a given type completed by an employee in a given time. Average time of completing given task by employee. - The lower the value of this indicator, the better.
3.	Task completion time	$W_{CRZ} = C / L_{ZR}$	minute/piece	C – total completion time of a given type of tasks in a given time. L_{ZR} – the number of tasks of a given type completed in a given time period. Average time of completing given task. - The lower the value of this indicator, the better.
4.	Additional work	$W_D = L_{ZD} / L_Z$ x 100%	piece/piece x % = %	L_{ZD} – number of additional tasks (out of the scope) completed in a given time. L_Z – number of all tasks completed in a given time. Percentage of additional work in total work.
5.	Additional work of employee	$W_{DP} = L_{ZDP} / L_{ZP}$ x 100%	piece/piece x % = %	L_{ZDP} – number of additional tasks (out of the scope) completed by an employee in a given time. L_{ZP} – number of all tasks completed by an employee in a given time. Percentage of additional work in total work for individual employees.
6.	Additional work time	$W_{CD} = C_{ZD} / C_Z$ x 100%	minute/minute x % = %	C_{ZD} – time of completing additional tasks (out of scope) completed in given time. C_Z – completion time of all tasks in a given time. Percentage of additional work time in total work time.
7.	Time of employee additional work	$W_{CDP} = C_{ZDP} / C_{ZP}$ x 100%	minute/minute x % = %	C_{ZDP} – time of completing additional tasks (out of the scope) completed by the employee in a given time. C_{ZP} – time of completing all tasks in a given time by an employee. Percentage of additional work time in total work time for individual employees (how much time an employee spends on additional tasks in relation to time spent on all tasks).

Cont. table 2.

8.	Punctuality (of employee)	$W_T = L_{ZNP} / L_{ZP}$ x 100%	piece/piece x % = %	L_{ZNP} – number of tasks not done on time by the employee for his/her own reasons in a given time. L_{ZP} – number of all tasks completed by an employee in a given time. Percentage of the number of overdue tasks in total number of tasks for individual employees. - The lower the value of this indicator, the better. We should aim for it to oscillate around 0%.
9.	Efficiency (of employee)	$W_W = L_{ZRP} / T_{EP}$	piece/h	L_{ZRP} – number of tasks of a given type completed by an employee in a given time. T_{EP} – employee effective working time in h (i.e. after taking into account the absences) in a given time. The number of tasks of a given type performed by a given employee during 1 hour of his/her work. - The higher the value of this indicator for particular tasks, the better (for an individual employee there will be as many indicators as the number of different types of tasks performed). Important! We do not sum up the indicator values because they refer to incomparable tasks. For individual employees, we can see how many pieces they produce for specific tasks within 1 hour of their work. It is possible to compare the performance of different employees for the same tasks.
10.	Work quality	$W_{JP} = L_{ZB} / L_Z$ x 100%	piece/piece x % = %	L_{ZB} – number of corrections made due to own errors in a given time. L_Z – number of all tasks completed in a given time. Percentage of work related to correcting own errors in the total work. - The lower the value of this indicator, the better. We should aim for it to oscillate around 0%.
11.	Employee work quality	$W_{JP} = L_{ZBP} / L_{ZP}$ x 100%	piece/piece x % = %	L_{ZBP} – number of corrections made by an employee resulting from his/her own errors in a given time L_{ZP} – number of all tasks completed by an employee in a given time. Percentage of work related to correcting own errors in the total work for individual employees. - The lower the value of this indicator, the better. We should aim for it to oscillate around 0%.

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THE DEMAND FOR QUALIFIED PERSONNEL IN THE PROCESS OF SOCIO-ECONOMIC TRANSFORMATION, DETERMINANTS AND CHALLENGES. CASE STUDY

Ryszard MARSZOWSKI[1*], Paweł OLSZEWSKI[2]

[1] Central Mining Institute National Research Institute Katowice; rmarszowski@gig.eu,
ORCID: 0000-0002-2855-7121*
[2] Central Mining Institute National Research Institute Katowice; polszewski@gig.eu,
ORCID: 0000-0003-3020-7670
* Correspondence author

It is not the strongest or the most intelligent who survive,
but those who respond best to change.
Charles Darwin

Purpose: the article, "The Demand for Qualified Personnel in the Silesian Voivodeship. Determinants and Challenges," is an attempt to diagnose the situation, but also to reveal trends and barriers that will be taken into account in the development of human resources in the Silesian Voivodeship.
Metodologia: the theses presented in the article were verified using the following methods: literature review, critical analysis of literature, analysis and comparison of documents and an example of good practices.
Results: research indicates that one of the key elements of the Silesian Voivodeship's sustainable development lies not only in economic transformation and adaptation to global megatrends, but above all in the conscious development of human capital. Human resources—understood as the pool of knowledge, skills, and attitudes of residents—are the foundation of the region's lasting competitiveness.
Research limitations/implications: the scope of data used in the research may not cover all identifiable directions and trends of sustainable development of the Silesian Voivodeship, but only those that appeared in adaptive analyses covering the purpose of the article.
Practical implications: in the process of social and economic transformation, the cooperation of three key spheres: science, economy and education is becoming a necessary condition for meeting the challenges related to decarbonisation, digitalisation, ageing society and changes in the labour market.
Originality: this article attempts to systematize the main determinants of demand for qualified personnel in the Silesian Voivodeship. We present not only current deficits and forecasts but also the broader socioeconomic context that influences career development in the voivodeship. Particular attention is paid to recommendations and best practices that can form the basis for

building a coherent and long-term human resources policy, taking into account not only the needs of the economy but also the ambitions and potential of the voivodeship's residents.
Keywords: transformation, qualified staff, case study.
Category of the paper: research paper.

1. Introduction

The Silesian Voivodeship has long been one of the most important industrial centers in Poland, but it is also a region particularly hard hit by structural and social changes (Regional Profile Silesia, Poland, 2024). Economic transformation, ongoing deindustrialization processes, and the pressures of global trends—such as digitalization, the green transition, and an aging population—are significantly impacting the local labor market. This dynamic and ambiguous landscape raises one of the key questions of contemporary regional policy: will the Silesian Voivodeship have an adequately qualified workforce to meet upcoming development challenges? The article, "Demand for Qualified Personnel in the Silesian Voivodeship. Determinants and Challenges", attempts to diagnose the current situation and identify trends and barriers that will impact the development of human resources in the voivodeship. The authors present data and analyses on professional deficits, demographic structure, the role of vocational education, and the mismatches between the education system and the actual needs of the labor market. Particular attention is paid to phenomena such as the outflow of young people, the low prestige of technical professions, and the lack of a coherent policy linking education and employment. This article attempts to systematize the key determinants of demand for qualified personnel in the Silesian Voivodeship. We present not only current deficits and forecasts but also the broader socioeconomic context that influences career development in the voivodeship. Particular attention is paid to recommendations and best practices that can form the basis for building a coherent and long-term human resources policy, taking into account not only the needs of the economy but also the ambitions and potential of the Silesian Voivodeship's residents.

2. The workforce of the future in a region of transformation

The Silesian Voivodeship is currently at a crucial moment in its history – a turning point where its industrial past collides with the demands of a modern, green, and digital economy. For decades, the region has based its identity on the mining sector, heavy industry, and large-scale production. These pillars, while still important, are now being gradually dismantled under the influence of global processes – decarbonization, automation, energy transition, and social

transformation. This represents not only a shift in the economic model but also a profound social transformation, affecting everyday experiences of work, education, interpersonal relationships, and aspirations. In this context, the workforce of the future is becoming much more than just a component of the employment system – it is a key actor of change (Talent trade-offs…, 2025). Whether the Silesian Voivodeship seizes its opportunity to transform into an innovative, green, and socially resilient region will depend on the quality, flexibility, and competence of the local workforce. Changing the employment structure – from heavy industry to knowledge sectors, specialized services, and green technologies – requires not only a restructuring of labor market institutions but also a fundamental shift in professional culture. From this perspective, social transformation means redefining the prestige of professions, overcoming multi-generational patterns of "full-time" work, as well as strengthening entrepreneurial attitudes, openness to change, and readiness for lifelong learning (Torrejón Pérez, Fernández-Macías, Hurley…, 2024). This is not only a systemic challenge, but also an identity one – the region must develop a new narrative about itself – as a place not of the end, but of a new beginning. The parallel economic transformation of the Silesian Voivodeship assumes a gradual shift away from exploitative, resource-consuming development models towards an economy based on sustainability, innovation, and knowledge. This is not only a necessity resulting from EU climate goals and global trends, but also an opportunity for long-term strengthening of the region's competitiveness and improving the quality of life of its residents. In this perspective, a new quality of human resources becomes a key factor – capable not only of operating modern technologies but also of co-shaping solutions that respond to complex social and environmental challenges (Green Deal…, 2025). The workforce of the future will have to function in a reality in which the energy sector is shifting towards distributed renewable sources, industry is focusing on automation and robotics, and the economy requires the ability to manage resources in a circular manner. The importance of professions related to wind energy, photovoltaics, and energy storage is growing, as well as those related to building energy efficiency, climate change adaptation, and the design of zero-emission urban infrastructure. In these areas, engineering and technical competencies, as well as the interdisciplinary ability to integrate knowledge from various fields, will be particularly important. At the same time, social sectors are gaining increasing importance: care for the elderly, healthcare services, environmental education, psychological and development support – areas where social, empathetic, and communication skills predominate. Such sectors, although often undervalued in traditional economic strategies, will constitute one of the pillars of a green and inclusive transformation. Industries related to digitization and mobility are also developing dynamically, particularly information technology, data analytics, artificial intelligence, low-emission logistics, and electromobility. They will create new professions and career paths, requiring both technical skills and critical thinking and adaptability. Therefore, the development of the workforce of the future cannot be left to chance. Strategic investment in vocational education, retraining and lifelong learning programs, a consulting system based

on market data, and closer cooperation between education, employers, and local governments are essential (Workforce of the future…, 2018). Only then will the region's residents be able not only to navigate the changing economic reality but also to become active co-creators of it. Therefore, today more than ever, we need a workforce understood as a collective potential for change – people who will not only respond to change but also co-create it. Their development cannot be left to chance – it requires a joint strategy between public institutions, the private sector, and education. A region undergoing transformation needs people capable of not only navigating the new order but also giving it meaning.

3. Changing needs of the labor market

As already noted, the Silesian Voivodeship is currently at the heart of strategic economic changes that are impacting the local labor market in ways unpredictable even a decade ago. Rapid technological progress, digitization, automation of production processes, and the green transformation are redefining the demand for skills, professions, and forms of employment. First and foremost, we are observing a dynamic decline in demand for traditional industrial professions: miners, steelworkers, and conventional machine operators. They are being replaced by new technical and engineering staff involved in the creation, operation, and maintenance of modern installations – especially in the renewable energy, automation, robotics, electromobility, and digital production systems sectors. These are no longer just engineers, but also technicians, PLC programmers (a PLC programmer is responsible for programming a programmable logic controller (PLC) to control it and implementing its functions in control systems), industrial cybersecurity specialists, data analysts, and supply chain and logistics specialists. In this perspective, service sectors are gaining importance, increasingly taking over the role once held by heavy industry. Care, healthcare, education, and environmental sectors offer employment opportunities not only for those changing career paths but also as alternative development environments. Here, demand for caregivers for the elderly, therapists, environmental educators, specialists in socio-ecological project management, and local change agents is growing. Transformation, a driving force, supports the development of technology industries, especially IT. A growing number of start-ups, software companies, competence centers of global corporations, and research and development centers are emerging in the region. This translates into an increased demand for programmers, specialists in artificial intelligence, cloud computing (an IT technology used to process and store data in a virtual space), data engineers, and UX designers (persons responsible for user experience design, i.e., designing user experiences in interaction with a product, most often digital, such as an app or website). This knowledge requires not only technical skills but also soft skills – creativity, teamwork, communication, and change management. The role of

transversal, digital, analytical, linguistic, and social skills is growing. Even in technical professions, the ability to critically analyze data, work with cloud computing, and be flexible and proactive in problem-solving is gaining importance. A case in point is provided by research conducted by the Voivodeship Labor Office in Katowice among companies operating in smart specializations. Employers hiring for specialist positions most frequently cited the need for computer software (31% – including specialized software), good English (19.3%), and programming skills (6.9%). At the same time, "soft" skills were highly valued: reliability and conscientiousness, quick learning (49%), efficiency in using work tools (42.8%), and problem-solving skills (40%). In terms of two-year forecasts, entrepreneurs predicted particularly growing demand for IT specialists and mechanics, while maintaining the requirement for experience and transversal competencies (including rationality of action 65.8%, learning speed 76.3%). This data comes from the report "Demand for qualifications/skills in innovative enterprises operating in the area of smart specializations against the economic background of Silesia" (VLO Katowice, quantitative and qualitative study; including N = 833 in the forecast module) (Demand for qualifications/skills…, 2021). This approach supports the emergence of new employment models, flexible contracts, remote work, and project work. The need to adapt to the changing needs of the labor market forces profound and systemic transformations in education – both formal, conducted in schools and universities, and non-formal education: courses, training, mentoring, and continuing education. The current education model, based on static knowledge transfer and a rigid division into educational and professional stages, is proving insufficient in the face of dynamic, multidimensional technological, social, and climate changes. This is confirmed by, among others, The experience of the Ruhr region (Germany) shows that long-term economic diversification requires parallel investments in research and development, culture, and the revitalization of post-industrial areas – from technology parks to social and educational functions. A consistent "three-pillar" policy proved crucial there: green infrastructure, knowledge clusters (e.g., energy, materials, logistics), and raising adult qualifications, supported by a dual education system. The lesson for the Silesian Voivodeship is the need to build lasting chains of cooperation between universities, local governments, and businesses, so that projects do not end with the financing cycle. In Asturias (Spain), the emphasis was on a gradual phase-out of coal through social contracts and "just transition" programs, combining protective benefits with active labor market policies; training vouchers and fast-track retraining for technical professions related to renewable energy sources and the maritime economy proved particularly effective. It is significant, however, that in Asturias, the slow modernization of small and medium-sized enterprises limited the absorption of new skills. This serves as a warning that in the Silesian Voivodeship, enterprises should be modernized in parallel (digitalization, automation, data management), not just by educating employees. The Ruhr region also stands out for the scale and quality of the revitalization of brownfield sites (mines, coking plants) into spaces for start-ups, cultural institutions, and public services; this demonstrates that spatial policy is a tool for the labor

market, as it shortens the gap between talent and employers. In both regions, local "competence centers" serving as brokers for training and internships increased their effectiveness – this solution could be transferred to the Silesian subregions by linking them with vocational schools and universities. Comparisons from the Ruhr and Asturias confirm that soft skills (teamwork, communication, change management) are just as critical as technical skills; programs should develop them from the secondary school level. A key success factor was stable funding – a mix of national and European funds – and multi-year, phased mine closure schedules, which reduced labor market shocks. At the same time, the Ruhr Basin demonstrates that without an active migration policy and "attracting talent", demographic decline is a threat. The Silesian Voivodeship should link transformation with improved quality of life (transport, housing, care services). Asturias offers a valuable model for developing related sectors (e.g., industrial and educational tourism) as a source of jobs that don't require long training cycles, helping people over 40 to smoothly transition into new paths. In both cases, strong social dialogue (trade unions, employers, local governments) minimized social costs. In the Silesian Voivodeship, this dialogue should also encompass the small and medium-sized enterprise sector and non-governmental organizations. The practice of "competency maps" is also a good point of reference – in the Ruhr and Asturias, regularly updated skill matrices allowed for precise matching of school and course offerings to demand forecasts. Finally, continuing education proved to be the foundation for the sustainability of the changes: the right to lifelong learning supported by flexible micro-qualifications and the validation of competencies acquired informally. A comparison of these experiences indicates that a hybrid model will be most effective for the Silesian Voivodeship: simultaneous industrial modernization, fast-track retraining, strengthening of social services, and intelligent urban revitalization that attracts investors and retains residents.

In the face of digital and ecological transformation, education must become more responsive, flexible, and future-oriented. A key task is to rapidly adapt core curricula and educational models to the realities of the Fourth Industrial Revolution. This means not only updating curriculum content with new technologies (e.g., automation, programming, AI, renewable energy), but also redefining teaching methods, with a greater emphasis on transversal competencies, project-based skills, critical thinking, and collaboration within interdisciplinary teams. Intensive, partnership-based collaboration between schools, universities, employers, and public institutions is also essential. Only in this way will it be possible to develop flexible educational and professional paths that meet the real needs of local labor markets. Apprenticeships, dual education, sponsored classes, and industry competence centers—these are tools that allow for the integration of learning with experience and the building of bridges between the world of education and the realities of economic transformation. At the same time, the importance of non-formal and informal education cannot be overlooked. The region's transformation requires the mass mobilization of adults, especially those affected by the transition away from heavy industry and mining. Access to retraining programs, digital

platforms for self-education, and systems for validating competencies acquired outside of school are essential to ensuring genuine social and professional inclusion in changing conditions. Finally, education must adopt a long-term perspective, extending beyond the current needs of the labor market. Its role is also to shape civic, pro-ecological, and innovative attitudes that will allow the region's residents not only to adapt to change but also to actively participate in its creation. From this perspective, the development of education is not a cost, but rather the most important investment in the region's future. In summary, the needs of the labor market in the Silesian Voivodeship are undergoing a profound evolution. The current model based on physical strength and industrial production is being replaced by a knowledge economy, green technologies, and social services. This is a major test for the education system, institutions, and local policy – whether they will be able to adapt to new realities and support the development of the workforce of the future.

4. Shortage qualifications and competencies with an emphasis on megatrends and forecasts

The Silesian Voivodeship, one of the most densely populated and industrialized regions in Poland, is currently undergoing a profound transformation – not only economically but also socially. This process, driven by megatrends such as automation, digitalization, energy transition, climate change, and an aging population, is directly impacting the structure of demand for professional qualifications and competencies. With ongoing decarbonization and transformations in the industrial sector, the region is increasingly experiencing competency shortages, particularly in the areas of new technologies, green professions, and social services. As numerous assessments (https://barometrzawodow..., 2025) show, the region's shortage professions are dominated by both specialist positions (e.g., electricians, automation technicians, mechatronics technicians, digitally controlled machine operators) and those related to the service sector (e.g., drivers, nurses, psychologists, caregivers for the elderly, and vocational teachers). The importance of so-called soft skills – the ability to collaborate, solve problems, adapt to change, and engage in lifelong learning – is also growing. Market forecasts and strategic documents indicate that the most sought-after qualifications will include digital skills (programming, data analysis, cybersecurity), engineering skills (automation, robotics, materials engineering), environmental skills (circular economy, renewable energy technologies), and social skills (care, education, mental health). Transversal competencies are also gaining importance – they connect various fields and enable functioning in complex professional environments (McKinsey Technology…, 2025). Competency deficits in the Silesian Voivodeship are becoming particularly dangerous in light of the growing dual structural challenge, which in the long term could undermine the region's development

potential. On the one hand, older workers are leaving the labor market at an increasingly rapid pace – representatives of the generation that for decades built the industrial backbone of the Silesian Voivodeship. These are often individuals with unique professional qualifications: technicians, electricians, welders, complex machine operators, energy engineers, and production masters. Their knowledge and experience are difficult to replicate in a short time, especially given the low number of successors in the same career paths. On the other hand, the younger generation is increasingly less likely to choose educational paths aligned with actual labor market demand, driven more by prestige or media trends than by employment forecasts. The popularity of humanities and general studies, coupled with a simultaneous decline in interest in vocational and technical education, exacerbates the problem of mismatches between qualifications and economic needs. This applies not only to secondary schools but also to universities, which are still insufficiently integrated with the socio-economic environment. The problem is further complicated by the insufficient number of vocational teachers and practical instructors, particularly in technical and industrial specializations. Many schools lack specialists who could impart modern knowledge and simultaneously inspire students to choose a technical path. Teaching staff often lack the latest technological knowledge or exposure to current industrial practices. The low prestige of the vocational teaching profession and insufficient systemic support lead to the disappearance of the competence chain of generations (Edukacja 2025, 2025). As a result, the educational and vocational system in the region lags behind the actual transformation processes. Without decisive corrective action – including support for educators, modernization of vocational education, promotion of shortage professions, and improved counseling – this threatens to perpetuate competency gaps and weaken the Silesian Voivodeship's position in the economy of the future. In the face of competency deficits and a dual generational challenge, reflection on the solutions used in the world's most advanced economies is particularly important. Countries such as the United States, Japan, Canada, Germany, and South Korea, facing similar challenges of an aging population and a shortage of technical specialists, are systematically investing in the development of the workforce of the future, treating human capital as a strategic resource for national competitiveness. One of the key measures in these countries is the strong link between the education system and the labor market, based on tripartite cooperation: schools, employers, and public institutions. In Germany, the dual model, combining education with work in a company, has become the foundation of vocational education (Haasler, 2020). In Canada and the USA, community colleges and short-cycle programs are developing dynamically, which allow for a quick response to local competence needs, especially in the technology and care services sectors (College Education in USA…, 2025). In Japan and South Korea, great importance is placed on continuous professional development and a culture of "lifelong learning", supported by the state and large enterprises. Reskilling programs and online courses certified by universities and technology companies (e.g., MITx, edX, Coursera) are standard tools for responding to the changing needs of the economy (Bradford, Park, Brown, 2024).

Moreover, many highly developed countries actively promote technical and social professions, which, despite their strategic importance, often enjoy lower social prestige. Canada and Germany have introduced nationwide information campaigns demonstrating the attractiveness of career paths, high quality of life, and development potential in sectors such as renewable energy, automation, caregiving, and technical education. These behaviors are characterized by one thing: proactive planning and long-term thinking about society's competency structure (Empowering people to act…, 2025). This is not just about responding to shortages, but also about shaping future needs and supporting informed educational and career choices. For the Silesian Voivodeship, which is also struggling with the outflow of young people and the lack of qualified staff, adapting these patterns may provide a real opportunity to build a lasting development advantage.

5. Determinants of the demand for qualified personnel with an emphasis on economic forecasts in the global dimension

The demand for qualified personnel, both regionally and globally, is shaped by a complex set of economic, technological, and social conditions. The section of the article devoted to the situation in the Silesian Voivodeship highlights that local competency shortages are not an isolated phenomenon, but part of a much broader trend resulting from global development megatrends and structural transformations in the global economy. Analyzing these determinants from a macroeconomic perspective allows for a better understanding of the directions in which the education system, labor market planning, and regional policy should develop. One of the most important factors determining future demand for personnel is the accelerating digital transformation. Globally, it is predicted that by 2030, nearly 75% of all jobs will require intermediate or advanced digital skills. Artificial intelligence, data analysis, process automation, software engineering, and cybersecurity will become the foundation of most sectors – from industry to education, healthcare, and transportation (Mikhalkina, Nikitaeva, 2022). As a result, the employment structure will shift towards technical, engineering, and analytical professions. The second key determinant is demographic change, particularly the aging population in highly developed countries. UN forecasts indicate that by 2050, one in four people in Europe and East Asia will be over 65 (Bloom, Luca, 2016). This phenomenon generates a growing demand for specialists in long-term care, geriatrics, health psychology, and social services. At the same time, in many regions of the world, there is pressure to increase the professional activity of women and people with disabilities – which also requires appropriate staff qualifications in supporting sectors (Securing the future…, 2023). Climate change and energy transformation are another factor, driving the development of the "green economy". The renewable energy sector (RES), energy efficiency, the circular economy,

and environmental engineering are areas where global investment is growing exponentially, and with it, the demand for specialists: designers, installers, engineers, auditors, and environmental advisors. According to a report by IRENA (International Renewable Energy Agency), by 2030 the number of jobs in the renewable energy sector worldwide will increase to over 38 million – which means a huge challenge for the education and retraining systems of the workforce (Securing the future…, 2024). In turn, geopolitical instability and the reconfiguration of supply chains following the COVID-19 pandemic and as a result of wars (e.g., in Ukraine) are increasing the importance of local and regional industrial competences (Bednarski, Roscoe, Blome, Schlepe, 2025). Strengthening production sovereignty in developed countries is resulting in the return of some production to home countries (reshoring), which in turn creates the need to rebuild human resources in traditional, yet modernly managed industries, such as metalworking, industrial automation, logistics, and quality. Global cultural and social changes are also noteworthy, as they are driving the growing importance of soft skills—relationship management, conflict resolution, adapting to change, creativity, and working in multicultural teams. In the era of remote work and project-based organizations, these skills are becoming as crucial as technical competences (Poláková, Horváthová, Madzík, Copuš, Molnárová, Polednová, 2023). All of the previously mentioned phenomena-technology globalization, energy transformation, demographic changes, digitization, and decarbonization – are also impacting the Silesian Voivodeship, whose historical industrial heritage is becoming both an asset and a challenge. The region cannot merely passively adapt to trends – it must proactively design the future of its human resources. This means moving away from the logic of "reactive training to address shortages" and toward strategic competence development based on forecasted labor market scenarios. In this article, we present five scenarios for the future of the labor market that could become the basis for planning political and educational activities in the region. The first is the scenario of technological dominance (automation and AI) (Imbusch, Steg, 2023). The labor market is dominated by technologies, in which some traditional professions disappear, replaced by new ones requiring advanced digital and engineering competencies. In this model, the Silesian Voivodeship must prioritize training specialists in fields such as programming, data analysis, automatic process management, and robotic systems engineering. A sustainable development scenario, in which the region's economy is transformed towards "green" sectors, determines the growing importance of professions related to renewable energy, energy efficiency, the circular economy, and adaptation to climate change (Soergel, 2012). Environmental, engineering, and management competencies, as well as the ability to work in interdisciplinary project teams, are becoming crucial. In a scenario based on services and interpersonal relationships, society is aging, and the importance of care, education, and healthcare services is growing (Thinley, 2021). The role of soft skills, such as empathy, communication, and interpersonal skills, is strengthening. The Silesian Voivodeship can capitalize on this scenario by developing regional centers for social and medical services and educating staff in modern forms of care and support. A novelty is the scenario of regional

economic sovereignty. In this scenario, the emphasis is on the geopolitical crisis and disruptions to the state's supply chains. This scenario results in a pattern where regions strengthen their local production potential. Industry is reviving, but in a modern, automated, and ecological form (Miró, 2023). Technical specialists, advanced production line operators, mechatronics engineers, logisticians, and leaders of technological change in small and medium-sized enterprises are needed. The fifth scenario is dominated by social inclusion and balance. Concern for social cohesion, combating exclusion, and activating those previously marginalized in the labor market are at the forefront. Social, coaching, adaptive, and intercultural competencies are becoming as important as technological ones. In this model, the demand for educators, career counselors, local facilitators, and HR specialists is growing. Each of these scenarios requires not only a different competency structure but also a different model of cooperation between schools, universities, employers, and local government. The workforce of the future—depending on which scenario materializes—must be not only technically well-prepared but also flexible, open to learning, and ready to fulfill various roles in the evolving work ecosystem. Therefore, the workforce development policy in the Silesian Voivodeship should be based on flexible, scenario-based forecasts, enabling not only reacting to change but also actively shaping it. It is precisely this ability to envision the future in various scenarios that will become the region's competitive advantage in a world of multidimensional transformation.

6. Conclusion - staff as a condition for sustainable development of the region

It seems that the sustainable development of the Silesian Voivodeship requires not only economic transformation and adaptation to global megatrends, but above all, the conscious development of human capital. Human resources – understood as the pool of knowledge, skills, and attitudes of residents – constitute the foundation of the region's lasting competitiveness. The collaboration of three key spheres: science, economy, and education is becoming essential to meeting the challenges of decarbonization, digitalization, an aging population, and labor market transformations. Cooperation between universities, the economic sector, and local governments must go beyond symbolic partnerships. Integrated platforms are needed, where science serves not only to generate knowledge but also becomes an active participant in socio-economic transformation – implementing innovations, training future specialists, and supporting enterprises in adapting to new realities. At the same time, the education system – from vocational schools to universities – should be refocused on flexible teaching models that respond to changing market needs and enable lifelong learning. It is worth identifying more specific policy tools that could translate the general assumptions of the transformation into

practical actions. First, incentives for technical education are essential – in the form of industry scholarships, tax breaks for employers co-financing vocational training, and the development of a dual system of learning and work. Second, programs are needed to improve digital skills, encompassing both industrial sector employees and those at risk of exclusion from the labor market. Such initiatives should combine practical training with modules on digital security, data analysis, and the use of new technologies in Industry 4.0. Another tool could be local industry competence centers, where universities, secondary schools, and businesses collaborate to run courses, research projects, and internships for students and adults. Grants and incentives for companies implementing employee retraining programs should also be considered, as should the creation of regional social innovation funds to support initiatives that engage older people, women, and migrants in the labor market. Finally, the development of flexible forms of lifelong learning – from micro-certificates and short courses to mentoring and online continuing education programs – is crucial. Such targeted policy measures will not only address the current challenges of transformation but also build the region's long-term resilience and ensure its residents have a real stake in creating a new economy. Sustainable development also means inclusion – activating groups at risk of exclusion and leveraging local social resources. In this context, investments in social, environmental, and technological competencies must be coordinated and based on a shared strategy of all regional stakeholders. Only then will it be possible to create a dynamic and resilient work ecosystem in which staff are not passive performers of tasks, but co-creators of innovative and responsible solutions. Therefore, staff are not merely a component of the system – they are its key driver. Their development is not a cost, but an investment in the future of the Silesian Voivodeship as a region of knowledge, collaboration, and sustainable growth.

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PERSONAL SAFETY VALUES OF PUBLIC SERVICE SECTOR EMPLOYEES IN THE BANI ENVIRONMENT

Ewa MATUSKA[1*], Wojciech PIESTRZYNSKI[2]

[1] Pomeranian University in Slupsk, Institute of Management; ewa.matuska@upsl.edu.pl,
ORCID: 0000-0003-1334-3574
[2] Pomeranian University in Slupsk, Institute of Security and Sociology; wojciech.piestrzynski@upsl.edu.pl,
ORCID: 0000-0002-0435-4557
* Correspondence author

Purpose: The main purpose of the article is to explore potential differences of personal values addressed to the sense of safety of public sector services (education and health care) employees in a current non-safe BANI environment. The practical aim is to use identified characteristics for revising/updating human resources managing strategies or tools in that sector into more adequate for changed work environment.
Design/methodology/approach: The theoretical part of the paper is based on critical analysis of domestic and foreign literature exploring the issue of the possible specificity of the values connected with perceived personal safety. It is focused on employees of public service sector which is especially overloaded with the characteristics of BANI surroundings. The empirical part shows the quantitative research and statistical analysis of data collected in late months of 2024 year via using CAWI experimental questionnaire. The sample (N = 196) were men and women employed in education and health care in Poland.
Findings: The results of the research are realized characteristics of preferred personal safety values of men and women employed in public service sector. The main finding is significant difference in higher evaluation of the value of "family security" in case of the women, both in education and in health care institutions. As in structure of employment in public service sector women are over representative, these findings should be taken into consideration in designing adequate HRM policy and strategies.
Research limitations/implications: The research reported is of exploration nature, and was done on a relatively small sample of employees. It should be continued as multisector comparative study to confirm realized gender differences.
Practical implications: The results allow to articulate some practical recommendations. The main is revision of traditional management approaches and methods currently used in public service sector, especially in area of HRM. It is recommended to switch into more human-center strategies, especially addressed to women.
Social implications: Current BANI environment creates the new kind of work related stress and challenges both work performance and work satisfaction, and public service sector plays critical role in crisis situations, like it was during covid-19 pandemics. Women dominate here in employment structure and need support via adequate HR strategies.

Originality/value: Studying specificity of personal values biased to the sense of safety of employees brings new implications for management in unstable reality and striving for organizational resiliency.
Keywords: personal values, public service sector, BANI environment, HRM strategy.
Category of the paper: research paper.

1. Introduction – values as navigators of managing in BANI environment

Values are important factors for people's lives and are formed out of people's principles and personal beliefs. Management by values is a classical concept how to integrate the strategic management with the human resources management system and organizational culture based on loyalty (Rokeach, 1983). In a case of employees of particular organization, the individual values are incorporated as the personal input to the package of organizational values, which are defined as the core for effective implementing mission and vision of the organization and mirror its statutory or commercial goals and aspirations. Personal and organizational values together build the organizational culture and create the work atmosphere inside the organization. Organizational culture, in turn, influences the overall strategic direction of management and indicate the main vectors for operation management within organization (Schein, 1992; Bogale, Debela, 2024). Especially, organizational culture impacts HRM policy and strategies. Values help to make decisions, establish priorities, estimate risks and align actions within members of the organization. They are the source of intrinsic work motivation, help to develop flexibility and easy adaptation in a demandable, complex, stressful and deadline work situations. Shared personal and organizational values create a positive impact on employee work satisfaction, as well as facilitate building strong relationships, productive collaboration and leadership. Identifying and maintaining the values improves decision-making and goal-setting processes and causes personal and professional growth of team members and leaders.

Special role at work plays employees' personal values associated with the perceived sense of safety (Nillsen, 2004; Gromek, 2021). They represents the kind of emotional values in organizational system (Krzakiewicz, 2012) and key part of employees' perceived workplace safety (Tomás et al., 2011; Ratilainen et al., 2016; Wawersik et al., 2023). The workplace safety perception is critical especially in a current turbulent times, marked by overlapping crisis situations – economic, political, humanitarian, climatic, and even biological, like it was well proved by global dangers created in times of Covid-19 pandemic.

The last pandemic crisis revealed not only the new biological global threat, but also the vulnerability of the business and public service institutions for new crisis situations. Obviously, pandemic especially hit the health care units. Medical staff was suddenly put as frontmen to fight with the new public health threat. No surprise that was this professional group was most hit by pandemic, with the highest rate of mortality and morbidity (Chutiyami et al., 2022).

The question is: what are the conclusions from that times about efficiency of crisis management, human resource management, or crisis resiliency of public service institutions? How they should act to be better prepared for the next possible massive threats or turbulences?

The insecure times are not gone, and since 2020 the world is described via using the new acronym BANI, what means the reality which is: B – brittle, A – anxious, N – non-linear, I – incomprehensible (Cascio, 2022). BANI environment widely and deeply impacts peoples' life and work. In domain of work space advocates to introduce new management approaches and strategies that relies on flexibility, empathy and the ability to operate under stressful and uncertain conditions (Mieszajkina, Ostapińska, 2024, p. 273). Important is to reassess organizational resilience (Weick, 1993; Linnenluecke, 2017; Hollands et al., 2024) and implement crisis management scenarios.

How to secure the organization in BANI environment via adjusting more adequate management models and strategies? There is no simple answer. The priority can be focus on strengthening the weakest, but most important attributes in the organization - human resources, and trying to elaborate more human-centric (Hector, Cameron, 2023) management approaches and strategies.

The main theoretical and practical purpose of that paper is to check how are prioritized general personal values connected with employees' sense of safety in a hard BANI work space, and investigate them on the sample of the men and women employed in education and health care institutions. The empirical study is conceptualized as the explanatory one, as it was not found in literature any similar.

The structure of the article is as follows. The first part provides the introduction to the study, followed by a chapter highlighting the notion of BANI environment and its implications for the management and work issues perception. The third section outlines the methodology and the data of the empirical study, while the fourth section presents the interpretation of obtained results along with their discussion. The paper is closed by a section summarizing the key insights and covers implications and recommendations to the area of strategic and human resources management, as well formulates some practical suggestions.

2. BANI environment challenges

Well accepted, traditional view for the organization as a complex and dynamic system implies to see it as closely interconnected with its environment (Krzakiewicz, 2012, p. 7). Thus, it is worth to study basic values which determine the organizational behaviour during ongoing crucial changes in organization's environment.

As it was already mentioned, the world of third decade of XXI cent. is described by acronym BANI, coined in 2020 by an American futurist Jamais Cascio in his article "Facing the Age of Chaos", where the particular letter means: B – brittle, A – anxious, N – non-linear, I – incomprehensible. Author summarized features of COVID-19 pandemic crisis and problematic post-pandemic reality, as well a set of unexpected, rapid changes and challenges put in front of the humanity. That cumulated experience involves the feelings of chaos, anxiety and helplessness, but also activates the need to define again one's self, looking for the sense of own existence, and take new ways of acting. More detailed characteristics of BANI reality are as follow (Miernik, 2023):

- B (Brittleness) - refers to the economy, energy instability, today's political systems and the environment, which can trigger a wave of further losses. The loss of one element causes further disruption and often catastrophic consequences. The fragility is mainly due to the lack of effective solutions to deal with the challenges and failures ahead. The future appears easily destructible and affected by many faults, which in turn could cause a number of problems globally.
- A (Anxious) - the brittleness of the world entails anxiety, and the overabundance of stimuli and factors subsequently minimize the sense of safety. The overwhelming amount of data and information today reaching people puts a great strain on their cognitive processes. Along with them comes fake news, which makes it difficult to sort and organize facts, and thus to plan actions rationally. Such a situation increases anxiety in almost every area of life, which leads to an unpleasant feeling of passivity and lack of causality.
- N (Non – linear) - modern reality and the incoming future blandly disrupt the logic of the cause-effect chain. Often even small and seemingly insignificant decisions entail a wave of broad, often global (both positive and negative) effects. This effect was particularly pronounced during the pandemic, which caused a series of unexpected, non-linear situations and changes. These affected economics, biology, medicine or transportation exponentially. One bad decision has triggered others, affecting many different groups in society. The lack of logic and unpredictability of the world reciprocally intensifies anxiety and misunderstanding, and leads to cognitive dissonance and chaos.
- I (Incomprehensible) - the aforementioned unpredictability, lack of linearity, fragility and inability to predict the consequences of events or decisions lead to a lack of understanding. It is increasingly difficult to argue and logically justify given areas. Many things and events lose their meaning. We lack schemes and resources, because despite these phenomena, the ability to understand the world remains unchanged.

Thus, although the future looks rather pessimistic, we should to be proactive and creatively try to build resilience against BANI world. In case of organizations it is the new task for leaders, managers, and employees. Adapting to the determinants of the BANI concept can be crucial to

achieving long-term success in a rapidly changing business environment which is full of uncertainty and serious global challenges. They are constantly broadening - from 2022 we have new war in a Europe caused by Russian military aggression against Ukraine, there is reactivated war conflict in Gaza region, instable political situation in many other countries, and from beginning of 2025 year - nonpredictable global geopolitical strategy of the new governance in US. All of it create totally new format of global insecurity which obviously impact individual sense of safety of citizens and employees.

Taking into account the current situation both in Poland, as global, we could conclude: indeed both the people and organizations are now intensively confronted with the BANI surroundings and have to meet demands of extremally problematic and stressful situations.

The question is if they are sufficiently prepared to deal with such challenges, both on individual as on organizational level? It is supposed that the new kind of management models, based on values should be useful here, such ones which put safety values into a central position of the organization. It is why, the exploration of values connected with sense of safety of employees working in BANI conditions was taken as the aim of own research presented in next parts of the paper.

3. Methods and research group

The research was conceptualized as a quantitative study based on the face to face survey's approach. As the research tool was used authors' questionnaire (experimental version modeled on the Milton Rokeach Scale, including timeless values). In the Rokeach Scale, the respondent makes the ranking of his/her personal values according to the individually perceived importance. In the study tool a rating was made using a Likert scale addressed to each value in such a way that the respondent can indicate the importance in his life of a certain value by marking on the scale only one answer via ranking as: 5 - very important value; 4 - important value; 3 - moderately important value; 2 - rather unimportant value; 1 - definitely unimportant value; 0 - neutral value; (-1) - anti-value; (-2) - definitely anti-value. In the research all responses were indicated on a scale from 5 to -1. A score of (-2) was not found. The research group was randomly selected from people of working age currently employed in a health and education public service sector. The final sample was constituted with total amount of 196 respondents. Surveyed subgroups were following: male education workers - N = 54; male health care workers - N = 46; female education workers N = 40; female health care workers N = 56. Study was conducted in a 4th quarter of 2024 year, in an office surroundings.

4. Results and discussion

Obtained results were elaborated with the use of statistical analysis, including ANOVA variance and Tukey's post hoc test. The tables below present the preference of general values connected with the sense of personal safety, like "world peace", „ national security" and "family security" among investigated employees (compared in diverse subgroups according to a gender and kind of employment place: education or health care).

Table 1a, 1b and 1c below describe the preference for the general value "world peace".

Table 1a.
Descriptive statistics for the dependent variable "value: world peace"

Grup	N	Min.	Max.	M	SD
men (M1)	54	(-1)	5	3.48	1.72
men (M2)	46	(-1)	5	3.95	1.29
women (W1)	40	(-1)	5	3.96	1.62
women (W2)	56	(-1)	5	4.05	1.26
Total	196	(-1)	5	3.85	1.48

M1 - men employed in education; M2 - men employed in health care; W1 - women employed in education; W2 - women employed in health care; N - sample amount; Min - lowest rank for the value, Max - highest rank for the value; M - mean score; SD - deviation score.

Source: own study.

Looking at data gathered in a Table 1a we see that the men employed in education (M1 = 54) have ranked the above value from -1 to 5, where the mean was M = 3.48 and SD = 1.72. Men from health care (M2 = 46) presented a value range from -1 to 5, with mean M = 3.95 and deviation SD = 1.29. Among women employed in education (W1 = 40), the results were distributed as follows: range of the value from -1 to 5, M = 3.96, SD=1.62. For women working in health care (W2 = 56), it was as follows: rank of the value from -1 to 5, M = 4.05, SD = 1.26. Collectively, the respondents (N = 196) ranked the value of "world peace " from -1 to 5, the mean score was M = 3.85 and the deviation SD = 1.48.

Summing up, the mean weight of the value "world peace" for all studied was at a moderate level.

Table 1b.
Analysis of variance in gender subgroups for the dependent variable "value: world peace"

Source	SS	df	MS	Test F	p
Between groups	10.35	3	3.45	1.59	0.19
Within groups	392.05	181	2.16	----------	----------
Total	403.05	184	----------	----------	----------

Source: own study.

The analysis of variance, expressed in F = 1.59 and p = 0.19 values (see Table 1b), means that in this case, the surveyed employees with a split between the male and female groups do not differ significantly in their perception of „world peace" as a timeless value.

The p-values of each pair of comparison, controlling also type of service institution-education or health care (Table 3c), indicate that M(1) vs. M(2) p = 0.39; M(1) vs. W(1) p = 0.46; M(1) vs. W(2) p = 0.18; M(2) vs. W(1) p = 0.89; M(2) vs. W(2) p = 0.89; W(1) vs. W(2) p = 0.89, that there are no significant differences between perceptions of the ”world peace” value in a case of employed in public service sector.

Table 1c.
Tukey's post hoc test for the dependent variable "value: world peace"

Pair of comparision*	Statisctic Tukey HSD Q	p value of Tukey HSD Q	Significance level
M(1) vs M(2)	2.22	0.39	insignificant
M(1) vs W(1)	2.06	0.46	insignificant
M(1) vs W(2)	2.87	0.18	insignificant
M(2) vs W(1)	0.05	0.89	insignificant
M(2) vs W(2)	0.46	0.89	insignificant
W(1) vs W(2)	0.36	0.89	insignificant

M1 - men employed in education; M2 - men employed in health care; W1 - women employed in education; W2 - women employed in health care; p - significance level.

Source: own study.

Table 2a, 2b and 2c present preference of investigated employees for the general value "national peace". The mean scores (see Table 2a) that the individual groups surveyed received M(1) = 52, M = 3.63; M(2) = 44, M = 3.97; K(1) = 31, M = 3.70; K(2) = 58, M = 3.79 as well as the total mean for N = 185, M = 3.77 indicate that national security as a value is located at a moderate level. The deviations of the results of the different groups were as follows - M(1) SD = 1.49; M(2) SD = 1.35; K(1) SD = 1.71; K(2) SD = 1.48 and total for all respondents SD = 1.48, indicating that both the studied groups of male and female employees are internally differentiated.

Table 2a.
Descriptive statistics for the dependent variable "value: national peace"

Grup	N	Min.	Max.	M	SD
men (M1)	54	(-1)	5	3.63	1.49
men (M2)	46	(-1)	5	3.97	1.35
women (W1)	40	(-1)	5	3.70	1.71
women (W2)	56	(-1)	5	3.79	1.47
Total	196	(-1)	5	3.77	1.48

M1 - men employed in education; M2 - men employed in health care; W1 - women employed in education; W2 - women employed in health care; N - sample amount; Min - lowest rank for the value, Max - highest rank for the value; M - mean score; SD - deviation score.

Source: own study.

The results of the analysis of variance (see Table 2b) and Tukey's post hoc test (Table 2c) clearly indicate that perceptions of value „national security" do not depend on the gender and place of employment (education versus health care) of the people surveyed; F = 0.44, p = 0.72 not significant, p for: M(1) vs. M(2) = 0.65 not significant, M(1) vs. W(1) = 0.89, not significant M(1) vs. W(2) = 0.89 not significant, M(2) vs. W(1) = 0.85 not significant, M(2) vs.

W(1) = 0.89, not significant W(1) vs. W(2) = 0.89 not significant. Thus, value of „national security" is a moderately important value in the perception of respondents.

Table 2b.
Analysis of variance in gender subgroups for the dependent variable "value: national peace"

Source	SS	df	MS	Test F	p
Between groups	2.97	3	0.99	0.44	0.72
Within groups	404.93	181	2.23	----------	----------
Total	407.91	184	----------	----------	----------

Source: own study.

Table 2c.
Tukey's post hoc test for the dependent variable "value: national peace"

Pair of comparision*	Statisctic Tukey HSD Q	p value of Tukey HSD Q	Significance level
M(1) vs M(2)	1.58	0.65	insignificant
M(1) vs W(1)	0.31	0.89	insignificant
M(1) vs W(2)	0.78	0.89	insignificant
M(2) vs W(1)	1.07	0.85	insignificant
M(2) vs W(2)	0.87	0.89	insignificant
W(1) vs W(2)	0.35	0.89	insignificant

M1 - men employed in education; M2 - men employed in health care; W1 - women employed in education; W2 - women employed in health care; p - significance level.

Source: own study.

Next tables, 3a, 3b and 3c reveal the data obtained for the general value "family security" which seems to be the most important value in everyone's life. Respondents indicated the above value as important (M = 4.41) and this time the different subgroups differed (see Table 3a). Men employed in education presented a score of M = 4.34, SD = 1.20; men in health care M = 3.95; SD = 1.42, women representing education M = 4.80, SD = 0.47; women working in health care had M = 4.62, SD = 0.87.

Table 3a.
Descriptive statistics for the dependent variable "value: family security peace"

Grup	N	Min.	Max.	M	SD
men (M1)	54	(-1)	5	4.34	1.20
men (M2)	46	(-1)	5	3.95	1.42
women (W1)	40	(-1)	5	4.80	0.47
women (W2)	56	(-1)	5	4.62	0.87
Total	196	(-1)	5	4.41	1.11

M1 - men employed in education; M2 - men employed in health care; W1 - women employed in education; W2 - women employed in health care; N - sample amount; Min - lowest rank for the value, Max - highest rank for the value; M - mean score; SD - deviation score.

Source: own study.

The above differences between the studied groups were confirmed by the result of variance F = 4.77, p = 0.003 (see Table 3b). The p-value indicates that the studied groups of employees differ significantly from a statistical perspective in locating family security as a timeless value. We further search, using the Tukey post hoc test (see Table 3c), also confirmed that the differences are always present, regardless of the pairs of subgroups compared.

Table 3b.
Analysis of variance in gender subgroups for the dependent variable "value: family security"

Source	SS	df	MS	Test F	p
Between groups	16.77	3	5.59	4.77	0.003
Within groups	212.17	181	1.17	----------	----------
Total	228.95	184	----------	----------	----------

Source: own study.

Table 3c.
Tukey's post hoc test for the dependent variable "value: family security"

Pair of comparision*	Statisctic Tukey HSD Q	p value of Tukey HSD Q	Significance level
M(1) vs M(2)	2.49	0.29	insignificant
M(1) vs W(1)	2.64	0.24	insignificant
M(1) vs W(2)	1.87	0.54	insignificant
M(2) vs W(1)	4.74	0.005	**p<0.01
M(2) vs W(2)	4.35	0.01	*p<0.05
W(1) vs W(2)	1.09	0.85	insignificant

M1 - men employed in education; M2 - men employed in health care; W1 - women employed in education; W2 - women employed in health care; p - significance level.

Source: own study.

The statistical analysis performed on the data about perception of the importance of general values such as world peace, national security and family security by employees in the public education and health services sectors revealed interesting results. In the case of preferences for general values world peace and national security, the respondents did not differ significantly among themselves. However, in the case of the value of family security, there are significant differences between men employed in education and women working in education (women value the value higher) also between men in health care and women working in health care (women value the value higher). These results indicate that the gender factor of employees is important and that it should be taken into account in various aspects related to the management of employees employed in the public service sector.

5. Summary

In a BANI work space employees can't predict what suddenly will happen both outside and inside organization. Public service sector serves to all community and its efficiency is crucial for dealing with massive crisis situations. On the base of own late experience (at least from covid-19 pandemic time) they can easily predict occurrence of possibility new stressful or even harmful events. Their individual and organizational sense of safety is thus minimized.

General values of public service employees, addressed to the sense of safety such as "world peace" and "national safety" in presented research were evaluated as moderately important, both in case of men and women. The full scaled war behind Polish eastern border which lasts over two years undoubtedly lifted these values on that relatively high level of preference.

The significantly higher rank was given to value “family security”, but exclusively in case of the women employed in public service sector. This result has to be seen as the signal of experiencing by women emotional fears and concerns about own family safety. Such tension also reflects evidence of occupational stress. Women filling their work tasks connected with serving other people, but during work they also are focused on the issue of the security of own family members. For sure it is the kind of role stress, one of types of work related stressors described in a classical theory of organizational stress (Kahn et al., 1964) and later elaborated as so called JD-R model (job demands and job resources), which today is a mainstream conceptual framework used in job stress and job burnout research (Demerouti et al., 2001). According to the JD-R model, job characteristics can be aggregated into two broad categories: job demands and job resources. Job demands refer to the material, psychological, social or organizational requirements involved in a person’s work that require continuous physical or psychological effort or skill, which in turn is related to certain physiological and psychological costs, such as job stress and role ambiguity.

We can conclude that in case of women employed in public service institutions (education and health care) and experiencing intense stress role connected with concerns about their family security, job demands are higher than job resources. Balancing this inequity is possible by two ways – to minimize job demands (what is aimless, as the job description in case of their workstations probably is accurate), or to strengthen job resources. The latter one seems to be more adequate and realistic. The operational question is only how to do it?

The answer should be done by formulating concrete proposals by HRM departments of organizations. But before, the leaders and decision makers should consider how to adopt their strategic management approaches into more human-centric and flexible, just - more adequate for BANI work conditions.

As women working in education and health institutions usually make up the majority of the workforce, the realized problem can’t be ignored. The feminization of such professions as teachers and nurses is well proved, and will be probably still existing. That suggests to consider implementing systemic solutions and take the interventions which possible will mitigate the realized higher vulnerability and weaker resilience of women for job role related stress. It can be for example the offer of specific benefits, like option of hybrid or remote work, flexible work schedules, assistance or support in caring over small children or depended people (for example older parents), possibility of taking sabbatical vacation, using coaching or mentoring, proposal of using variety of work – life balance and health support programs. Such interventions not only should help to survive employees in a problematic BANI environment, but also in a long -term perspective can positively strengthen the organizational resilience capacity.

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QUALITY OF SERVICE FOR INDIVIDUAL CUSTOMERS INTERESTED IN OPENING A BANK ACCOUNT FOR A CHILD IN POLAND

Alina MATUSZAK-FLEJSZMAN[1*], Sebastian ŁUKASZEWSKI[2]

[1] Uniwersytet Ekonomiczny w Poznaniu; alina.matuszak-flejszman@ue.poznan.pl,
ORCID: 0000-0001-5588-9343
[2] Akademia Nauk Stosowanych w Koninie; sebastian.lukaszewski@konin.edu.pl,
ORCID: 0000-0001-6802-9107
* Correspondence author

Purpose: The article aims to discuss and analyze the research results on the quality of customer service for an individual interested in opening a bank account for a child.
Design/methodology/approach: The customer service quality research was conducted over three consecutive years: from 2022 to 2024. In each year, a total of 390 audits were carried out across 13 banks (130 conversations in own and partner branches, 130 telephone conversations with call center employees, and 130 email inquiries).
Findings: The study results revealed significant differences in customer service approaches among the banks. In some of the banks examined, a high level of employee engagement was observed in providing solutions that meet customer expectations. The quality of individual customer service in banks has been systematically improving over the three years of the study. The findings enabled the identification of the best banks in terms of customer service quality for clients interested in opening an account for their child.
Research limitations/implications: The study was limited to Polish banks and may not be fully generalizable to other markets. Future research could extend the scope by including international comparisons.
Practical implications: Advisors' ability to provide precise answers regarding the account and its related functionalities has a direct impact on customer trust and the final decision when choosing a bank. The analysis of the quality of children's account offerings, conducted based on selected parameters, allows for the formulation of recommendations for bank management: investing in advisor training, standardizing offer communication across all available sales channels, and implementing internal monitoring of service quality for products intended for children.
Social implications: Improving service quality can enhance financial accessibility and convenience of access to financial services for children across different age groups.
Originality/value: Service quality is a key factor influencing the assessment of an offer's attractiveness. As the study results show, even the best-structured offer loses value if the advisor is unable to present it properly or lacks knowledge of its basic conditions. A crucial aspect in evaluating a bank's offer is the quality of service across all sales channels. While a well-tailored offer makes this task easier, inadequate customer service—especially considering that the end customer is ultimately a child—means the attractiveness of the offer will not be fully

appreciated. The findings highlight that a professionally conducted advisory conversation can significantly influence the client's decision and foster long-term relationships with the bank. The conclusions drawn provide valuable guidance for bank managers in improving service standards for clients interested in opening a child's account.
Keywords: quality of banking services, quality of bank customer service, child's account.
Category of the paper: Research paper.

1. Introduction

A child's account has long been a vital banking product for parents seeking to introduce their children to the world of banking. Until now, it has been challenging to identify the factors that influence the quality of service for individual customers interested in opening an account for their child. The lack of research in this area was the main reason. Existing studies focused solely on comparing bank offers.

Therefore, in 2022, research was undertaken as part of the "Institution of the Year" project (https://mojebankowanie.pl/instytucja-roku) to assess the quality of service for customers interested in opening an account for their child. This research continued until 2024. The scope of the study, on which the analysis of banking service quality was based, covered three consecutive years. The topic of service quality for customers interested in a child's bank account is new, so steps were taken to explore this area. The broad scope of the quality studies, combined with their three-year duration, provided the basis for the authors' analysis of the results.

This publication assesses the quality of service provided to individual customers interested in opening an account for a child in thirteen selected banks in Poland. These banks acquired the most customers and accounts in 2024 and serviced over 49 million individual customer accounts at the end of 2024 (Ranking results, 2025).

Increasing competition requires financial institutions to develop high service standards and continuously improve the quality of service for customers interested in opening an account for their child. Increased competition means that one of the most critical factors influencing long-term and lasting relationships between organizations and customers is top-notch customer service. Efforts to improve customer service quality are often less costly (Witek, Nestorowicz, 2011), but they also represent a significant source of competitive advantage in the banking sector (Spyra, Piotrowski, 2010).

A professional approach by bank employees to the quality of service offered to children is essential. Otherwise, if the bank used by parents fails to provide adequate service, they are likely to open an additional account at another bank to ensure the child receives the appropriate standard of service. This could lead to parents switching banks in the long run.

A UK study analyzing satisfaction scores of 16 banks hypothesizes that banks receive lower satisfaction scores from their customers who also use the services of another bank, compared to customers who use the services of only one bank (Dawes, 2024).

To date, the literature on the subject has found research results on the impact of access to banking services in primary schools on students' financial knowledge and attitudes. Students who were encouraged to bank exhibited more positive opinions about banking services and gained more financial experience (Collins, L'Esperance, Odders-White, 2018). The presence of banks in schools increased students' awareness of financial services and improved their perception of banks (Collins, L'Esperance, 2023). There is also research examining children's knowledge status based on whether they have a bank account. Based on research commissioned by the National Bank of Poland, it was found that students with a bank account and savings achieved higher scores on the Economic Competence Index (the Economic Competence Index was developed in 2014, an indicator used to objectively measure the state of economic knowledge and skills of children and adolescents). Most students considered economic knowledge necessary in everyday life, but only a small percentage found it easy to understand (Diagnoses…, 2022). A 2022 study found that 15-year-olds in Poland scored relatively high in financial literacy compared to their peers in other countries. Poland is one of seven countries where students achieved an average score significantly higher than the average of the OECD countries participating in the study (Sitek, Wasilewska, 2024).

Research conducted in the United States suggests that teenagers' access to an independent bank account can be beneficial. Both custodial and independently held bank accounts enable teenagers to manage their cash flow, transfer funds, and save money. Independent accounts allow teenagers to exercise greater control because they also place the responsibility of managing money on the teenager, rather than their parents, creating opportunities for young people to learn about finances (Collins, Larrimore, Urban, 2021).

To the extent that children have positive initial experiences with the formal banking sector, they may develop a stronger preference for using formal financial institutions in the future (Brown, Cookson, Heimer, 2019).

It should be emphasized that the literature does not provide comprehensive research on the factors influencing the quality of banking services for individual customers interested in opening an account for their child. Therefore, it is essential to answer the following research questions:

RQ1: What factors determine a parent's choice of a given bank to open an account for their child?

RQ2: What influences the indication that a given banking offer is the most beneficial for a child?

RQ3: Does the quality of banking services change when it comes to offerings for children, and if so, to what extent?

Neither in Poland nor abroad has there been any research conducted on the quality of customer service for customers interested in opening a child's account. This topic was explored through our research conducted over three years and interviews with bank representatives. Based on our analysis, we identified factors that influence the quality of banking services. These include (Matuszak-Flejszman, Łukaszewski, 2022):

- credibility and trust in the bank,
- modernity of the bank, aesthetics and modernity of the branch interior,
- courtesy and friendliness of staff, manner of greeting and/or saying goodbye to staff,
- understanding of customer needs by employees,
- empathy,
- intuitiveness of the transaction service,
- speed and efficiency of customer service in branches,
- efficiency of customer service via the hotline,
- efficiency of service delivery via the transaction service,
- level of staff competence,
- staff communication skills,
- breadth of banking services offered,
- access to free ATMs,
- image of the bank,
- parking is available at the branches,
- branch opening hours,
- availability of branches in the area of residence,
- level of account maintenance fees,
- interest rates on savings, loans, and credits,
- amount of other fees and commissions,
- customer’s security at the bank,
- transparency, completeness, and reliability of information about banking services.

After analyzing the factors affecting the quality of banking services, we identified factors that impact the quality of service offered to children in two age groups: accounts for children aged 13 to 18 and accounts for children under 13.

The research conducted during this period can serve as a recommendation for many bank managers, as it provides a comparison with competing banks and identifies areas requiring improvement in service quality.

2. Children's bank account requirements and the role of customer service quality

Banks offer a variety of children's bank accounts depending on the age of the child as a prospective client. This is due to the legal provisions in this area and their varying interpretations.

According to Polish law, a child is any human being from conception to the age of majority (Journal of Laws 2023, item 292). According to this law, a person who has reached the age of 13 may have an independent bank account, as this is when they acquire limited legal capacity.

Polish banking law permits banks to maintain savings accounts, current accounts, or term deposit accounts for minors, provided they have reached the age of 13. They may freely dispose of the funds held in these accounts unless their legal representative objects in writing (Journal of Laws, 2024b). This is also confirmed by the provisions of the Civil Code (Journal of Laws, 2024a).

This doesn't mean, however, that you can't open an account for a child under 13. In such a case, the account is linked to the parent's account. The parent (or their legal representative) signs the bank account agreement, and the account thus becomes legally the parent's account. Most banks in Poland offer this solution. However, some banks don't yet provide this solution.

Legal regulations restrict children under 13 from having independent bank accounts, requiring that such accounts be opened and managed by their parents. For children aged 13-18, banking options provide partial autonomy while still being under adult supervision.

In Germany, children can open accounts from the age of 7, provided they have parental consent. Minors under 18 can usually open or close a current account only with the permission of both parents. To open an account, the credit institution requires appropriate proof of deposit (Was ist bei Girokonten…, 2024). In Belgium, France, or Italy, there is no statutory minimum age requirement for opening a bank account for a child (Age at which a child can open a bank account, 2018). In Belgium, for example, banks set their own rules regarding the age and access of underage customers to accounts. Therefore, the legal framework for children's accounts varies across countries, making it difficult to find models for changes to legal regulations in Poland.

In Poland, parents have the right to manage their child's assets under ordinary management, which also includes funds held in the child's bank accounts. For children aged 13-18, who have limited legal capacity, the provisions of the Civil Code and banking practices are crucial. The Polish Family and Guardianship Code (KRO) also lacks a precise definition of the amount that constitutes the limit of "ordinary management". Instead, the concept of "ordinary management" refers to the type of activities and their nature, rather than specific monetary values (Journal of Laws, 2023). For this reason, banks' approaches regarding amounts and limits vary, affecting the development of banking offers for children of different age groups. Most banks offer accounts for children aged 13 to 18. However, the selection of offers for children under 13 is somewhat limited.

The customer plays a crucial role in assessing the quality of banking services, as they are the most critical reviewers of banking offers and their presentation. Therefore, measuring customer service quality is a significant challenge for bank management. Marketing research plays a crucial role in this regard, as it enables the understanding of customer expectations and verifies the quality of services provided (Giemza, 2011). It is imperative to confirm whether, and to what extent, the quality of banking services changes when it comes to offerings to children. Bank managers should incorporate customer satisfaction research findings into their quality improvement efforts and improve customer relationship management. It is essential to highlight that customer knowledge, customer retention, and customer culture are the most crucial dimensions of service quality in the banking sector (Al-Tamimi, 2017). Therefore, to improve the quality of banking services and customer relationship management, research is commissioned on the quality of banking services, including those offered to children.

Measuring service quality is only possible when linked to the customer's actual perception. This is important because, due to the intangible nature of financial services, customers do not purchase the product itself, but rather the expected benefits (Payne, 1996). Customer service quality is often defined in terms of customer needs and expectations. However, this is not the only path to success. Effective customer service quality should not rely solely on striving to meet customer requirements and expectations, but also on accurately anticipating and exceeding them (Shaw, 2001).

Organizational management must consistently meet customer requirements by communicating effectively and building strong relationships with them to enhance service quality (Matuszak-Flejszman, Łukaszewski, 2022a).

When assessing the quality of service for customers interested in opening a bank account for their children, it is essential to consider the customers' natural needs related to other products, accessibility, security, and ease of payment management and use. A mobile app is a natural way to integrate these needs.

We live in a changing environment, and most matters are handled on mobile devices. A bank's mobile app should support customers in handling financial issues and payments at every level (Matuszak-Flejszman, Łukaszewski, 2022b). For children, the app becomes a new form of top-tier financial education, introducing them to the world of modern economic and technological solutions. For parents, it provides control over their child's finances while ensuring a high level of security.

During discussions about children's accounts during research, other products and additional features (e.g., savings accounts) also arise. From a service quality perspective, this is a significant indicator for bank managers. If a bank doesn't offer such solutions for children, it signals not only a need to modify its offering but, above all, a need to change its approach to the quality of service for this type of customer. Such changes should be continuously analyzed, listening to the customer's voice.

3. Research method

Bank managers employ a range of methods to gather information on customer service quality, including surveys, interviews, customer conversation reports, and direct conversations. One of the best ways to obtain such information is through mystery shopping combined with post-study focus group meetings (as evidenced by numerous studies conducted as part of Institution of the Year projects over the past 10 years). The focus groups were attended by the clients who conducted the study. The most crucial element in a successful customer satisfaction management strategy is the ability to listen and understand customer feedback.

Customer service quality studies were conducted in three consecutive years: from 2022 to 2024, using a traditional expert approach (as part of the Institution of the Year project), with a total of 390 audits conducted each year at 13 banks (130 interviews at own and partner branches, 130 telephone calls with bank hotline staff, and 130 email inquiries).

The customer service quality assessment framework for the study is presented in Figure 1. Each customer interviewer completed one survey at each of the selected banks. This study design provides additional comparative opportunities, as each customer interviewer is familiar with the services offered by all the banks surveyed. This is valuable for focus groups in which customer interviewers participate.

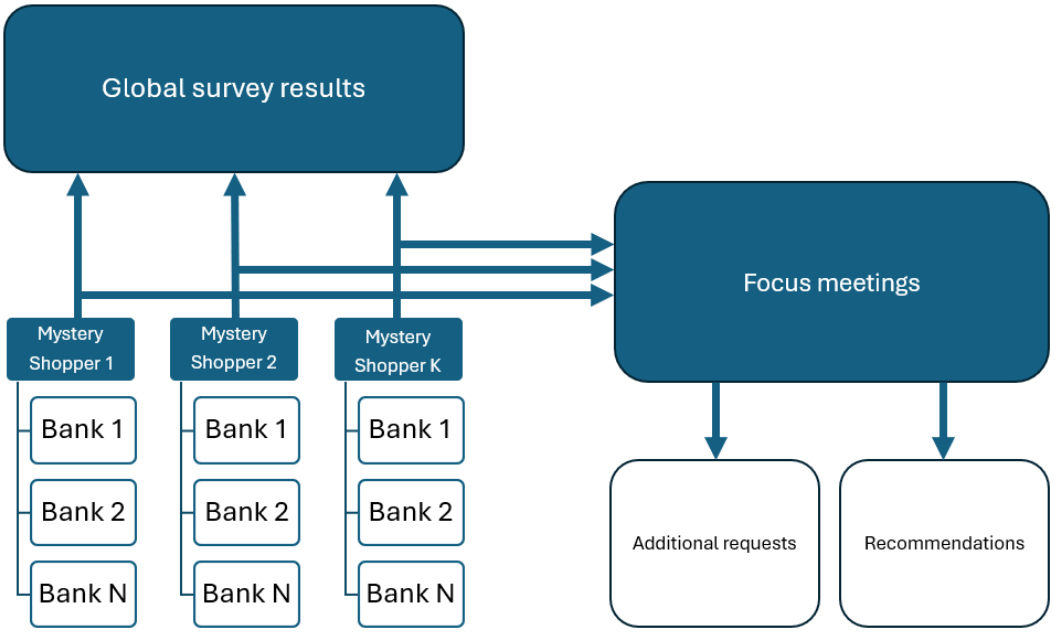


Figure 1. Diagram of the study on the assessment of customer service quality for clients interested in a child account ("K" denotes the number of customers conducting the evaluation, "N" denotes the number of banks surveyed).

Source: Own study based on research during the 'Institution of the Year' project.

Diagram of the study on the assessment of customer service quality for clients interested in a child account ("K" denotes the number of customers conducting the evaluation, "N" denotes the number of banks surveyed). A study of the quality of service for customers interested in opening a personal account for their children encompasses all aspects of the customer's interaction with the bank, including the entire process. The study aimed to assess the quality of service for customers who contact the bank through visits to bank branches and remote channels, throughout all phases of the service process, and who intend to open accounts for their children. In a bank branch, this process extends from the moment the customer enters the bank, through individual service elements at the branch, to the moment they decide to open an account. In remote channels, this process begins with the waiting time for a connection or the waiting time for a response after sending a question to the account opening proposal. The study results enabled a more accurate comparison of service quality across all banks and informed subsequent focus group discussions. We verified the quality of customer service for customers interested in opening a child account at the following banks: Alior Bank, Bank Pekao, Bank Pocztowy, Bank Millennium, BNP Paribas Bank Polska, Bank Ochrony Środowiska, Credit Agricole Bank Polska, mBank, PKO Bank Polski, Santander Bank Polska, Nest Bank, and VeloBank (Getin Noble Bank in 2022).

The study sought answers to questions regarding the quality of customer service for customers interested in opening an account for their children under 13 and for children over 13.

Additionally, focus group meetings were held after the survey, during which surveyed customers shared their impressions of their interactions with the bank. Additional conclusions from the subjective assessments of survey customers provide valuable supplementary information in the field of quality management, offering insights for the design and improvement of various processes.

4. Results of the service quality survey for individual customers interested in opening an account for a child

4.1. The scope of the study and the characteristics of the elements influencing the assessment of customer service quality

The three-year timeframe of the research conducted on the quality of service for customers interested in opening accounts for their children allows for the observation of trends in bank management's actions to improve customer service quality and the appropriate approach to the issue of child accounts and related products. The research conducted as part of the project identified service quality factors that influence the overall survey result, as well as additional factors that do not impact the global ranking of banking service quality. Each annual survey determines a percentage level of customer service quality, based on which banks are assigned to one of three categories.

The first category includes banks with scores between 80% and 100%, indicating very high customer service quality. The second category covers scores from 70% to below 80%. The third category includes banks with scores below 70%, indicating lower service quality. These criteria and the scored elements remained constant in each annual survey. This allows for comparison of this data across the study periods.

The survey of service quality for customers interested in opening personal accounts for their children covers the basic elements of a customer's interaction with a bank, including:

- employee professionalism and attitude,
- substantive competence,
- account opening processes,
- accessibility of information,
- financial terms and account features,
- atmosphere and comfort of service,
- overall satisfaction and willingness to recommend.

The elements and scope of the study, assessing the quality of service for a customer interested in opening an account for a child, are presented in Table 1.

Table 1.
Elements and scope of the survey assessing the quality of service provided to customers interested in a child's account.

Survey Elements	Detailed scope of the study
Employee Professionalism and Attitude	- feeling of being served by an expert advisor, - advisor's commitment.
Substantive Competencies	- showing the range of offerings for children, - the offer is presented in a way that makes it seem interesting.
Account Opening Processes	- sales attitude.
Availability of Information	- understandable transfer of information.
Financial Terms and Account Features	- information about the costs and limitations of the offer.
Atmosphere and Service Comfort	- impression after entering the facility.
Overall Satisfaction and Willingness to Recommend	- be willing to be served by this advisor again.

Source: Own study based on research conducted as part of the "Institution of the Year" project.

When assessing the professionalism and attitude of the employee, the expert's sense of service and the advisor's commitment are assessed, including the advisor's courtesy and personal manners, patience, empathy in conversation with parents, ability to clearly explain the terms of the offer, and willingness to provide comprehensive answers to questions posed during the meeting. When assessing professional competence, attention is paid to the range of services offered to children, particularly knowledge of the child's account details, familiarity with related regulations, and the ability to provide tailored advice based on the child’s age and needs. The account opening process evaluates the sales approach, which is influenced by factors such as clear guidance on required documents, the speed and efficiency of service, transparency, the absence of unnecessary formalities, and account opening options. Information accessibility is assessed by the clear communication of information, particularly regarding the offer, fees, limits, and rules of account use. Information regarding fees for specific features, their

availability, and security is essential in financial terms and account features. When assessing the atmosphere and service comfort, the customer's impression upon entering the facility is evaluated by analyzing wait times and the comfort level within the facility during the meeting. The assessment of overall satisfaction and willingness to recommend concerns a comprehensive evaluation of the visit, as well as the likelihood of recommending the bank to other parents.

In both sales channels, the purpose of the contact was to obtain information on whether and under what conditions children could use banking services. Customers were primarily interested in offers for teenagers, but they also inquired about accounts for younger children, under the age of 13, to differentiate between offers for children under and over 13. Nine main elements were assessed overall, contributing to the global score:

- Willingness to be served by this advisor again.
- Impression upon entering the facility.
- Information about the costs and limitations of the offer.
- Clear communication of information.
- The offer is presented in a way that seems interesting.
- Demonstration of the range of services for children.
- A sense of being served by an expert.
- The advisor's commitment.
- Sales attitude.

A summary of the factors influencing the evaluation at the bank branch, as presented in the 2024 study, is shown in Figure 2.



Figure 2. Summary of the factors influencing the evaluation at the bank branch in the most recent 2024 study.

Source: Own study based on our own research during the 'Institution of the Year' project between 2022-2024.

The survey revealed that the overall assessment by customer-interviewers at six banks was very high. The first impression upon entering the branch, as well as the way information was delivered, received the highest ratings. However, at nine banks, problems were identified related to the level of expert service and the sales attitude of advisors. During focus group meetings, customer-interviewers also highlighted a low level of sales engagement and the way the offer was presented, which in many cases was considered unattractive. It was noted that the positive reception of an offer was determined not only by its scope but also, and more importantly, by its presentation. There were instances where even a less competitive offer was well-received thanks to a professional conversation. Problems also arose with providing accurate information regarding the costs and limitations of the offer.

We also examined several additional elements that do not impact the service quality ranking, but provide vital information for bank managers. This information includes, among others, elements related to the offer, establishing a relationship with the bank, using the mobile app, cash, foreign currency payments, online shopping, depositing money, and topping up a child's account. These elements are essential to customers and were asked about during meetings or hotline conversations. Such information is valuable for bank managers, guiding them in improving both the offer and the quality of service.

Both at branches and via the hotline (Fig. 3), customer-interviewers sought the same level of information. Seeking information on service quality, they expressed interest in the basic parameters of the offer and asked detailed questions about their children's financial options. The customer-interviewers explored options for using funds via debit cards and BLIK. BLIK is a Polish mobile payment system that enables fast and secure payments in stores, online, at ATMs (https://www.blik.com/en/first-steps-with-blik), via phone payments, and with euro payment options. It also includes payment limits imposed by law or internal bank regulations, as well as parental control mechanisms.



Figure 3. Summary of the factors influencing the evaluation of the helpline in the most recent 2024 study.

Source: Own study based on our own research during the 'Institution of the Year' project between 2022-2024.

Research indicates that the quality of service for those interested in a child's account continues to improve year after year. In many interactions, the description of this offer resembled a standard personal account for an adult. Most of the information was provided by advisors without requiring any additional questions. Sometimes, clients even receive a comprehensive needs analysis that outlines the expectations of both the child and the parent. Unfortunately, some clients still received only fragmentary information, without being asked any additional questions, often limited to the slogan "everything is free". Obtaining comprehensive information required extensive clarification to get the answers. The best-prepared advisors distinguished themselves not only by a straightforward conversational approach but also by an appropriate level of product knowledge. Nuances such as the availability of payments by phone or watch, payment limits (or lack thereof), and mobile app options are crucial in offering to children. However, in many conversations, difficulties arose in establishing basic information or expanding on the slogan "everything is free". While answering customer questions, this often resulted in the discovery that child-specific offers did incur costs (e.g., for cash access). A good way to present a product to a customer is to compare the offer for an adult customer with an account for a teenager. After determining that the customer already had an account, some advisors described child-specific solutions by comparing what was available and what was not.

In addition to progress in customer service quality, the Polish market is also witnessing an expansion in the range of services, particularly for younger children under the age of 13. Offers for children aged 7-13 are now available at nine banks, but children can only obtain a card enabling in-store payments at eight banks. Depending on the offer, the card is either assigned to the child's account or has a separate card account assigned to the parent, which requires topping up. Bank Pekao and Bank Millennium continue to offer the most options for children aged 7-13. Only these banks provide an app with BLIK functionality in addition to an account with a payment card.

BLIK is a particularly desirable service because, given the age restrictions for mobile payments, it enables payments without the need for a card.

A significant limitation in offers for children under 13 is the very low limits on card payments, as indicated during the focus group research.

Customers during focus group meetings also pointed out that this solution is impractical. For example, a child wanting to buy a computer game would be unable to pay for it themselves. If a child at camp wanted to buy two servings of ice cream and an additional meal in one day, they might encounter limitations resulting from this payment limit.

Teenage offers are significantly less diverse in terms of the most basic features. However, after delving into the details of each bank's offering, it may turn out that, for example, mobile payments are not available at all, as the terms and conditions stipulate their use only by adults. Variations also apply to the availability of multi-currency services and the app's currency exchange service.

Legal restrictions on the use of bank account funds are a significant concern. Depending on the bank, the legal limit is either defined as an amount or stated in the terms and conditions, without specifying a monthly limit. Sometimes the limit applies to the child's use of funds, and sometimes only to the parent. This limit isn't inconvenient for everyday account use, but a teenager may be disappointed, as the limit prevents payments for more expensive items. If a child wants to deposit their savings in the account, the limit can practically prevent access to the funds.

There is a lack of a unified approach to this issue in the banking market. Particularly in banks that don't have a defined monthly limit, there was a lack of awareness that some offers included such a limit. Employees of the banks surveyed sometimes struggled to answer the question of whether a given bank has any restrictions, which is a fundamental issue regarding service quality.

4.2. Transfer of the offer and its presentation during visits to the facility

A key factor influencing the quality of a banking service is the way the offer is presented. It must be understandable to the customer. The scope of functionality and the offer itself, if poorly presented by a bank advisor, influence the assessment of the offer's attractiveness. Advisors must have a thorough understanding of the product and its associated functionalities.

Furthermore, the way the banking offer is presented is crucial, requiring a well-developed bank-wide concept. For example, according to the study, presenting the offer clearly and understandably is also vital. The way the range of services and their functionalities are presented to children of different ages is also crucial. A bank may have a well-developed offer for children, but a lack of advisor knowledge and limited presentation ideas will make it unpopular. Every customer who reaches out to the bank, whether through the hotline or by visiting a branch in person, must be convinced that they have found an interesting offer for their children. Therefore, offer modifications should be paired with a well-thought-out presentation and sales approach. Without this approach, you can have a great offer and still be perceived as the worst bank in the eyes of customers. Differences in customer service quality across the same banks, but across different contact channels, confirm that the perception of an offer depends mainly on the quality of service. The way it is presented is an essential element of success. Here, we can compare the presentation of the offer across two different sales channels: the hotline and the branch. The leading branch in the study received very low ratings from the "mystery shopper" during the hotline contact. This is an example of a bank that has offered an excellent deal to children of all ages for years. Hotline customers do not appreciate a good offer due to the poor quality of the conversations they have. A similar difference occurred within the same bank in other cases, for example, at ING Bank Śląski.

At VeloBank and Bank Millennium, the excellent quality of hotline service during branch visits was also rated much lower. The scope of functionality is also perceived differently when comparing the hotline and branch services. The customer's perception of the presented solutions as an interesting offer for children differs after a hotline conversation compared to a visit to the branch. This demonstrates differing customer service approaches across different sales channels and differing product perceptions. A lack of consistency in customer service across channels can lead to customer dissatisfaction and a loss of trust (Pawłowski, Pastuszak, 2019). Customers expect a consistent shopping experience regardless of the channel they choose, and differences in service can impact their satisfaction and loyalty (Nieżurawski, Pawłowska, 2017). This is also related to the lack of appropriate training for advisors in a specific sales channel.

A consistent level of service quality was observed across both channels (in-branch and on the hotline) at two banks, where a thoughtful approach to both hotline and in-branch conversations was evident.

For many parents, the reliability of information provided regarding children's banking services is a significant factor influencing their decision about the quality of these services.

Figure 4 presents the parameters of the basic elements of the offering that are important to parents, as well as the assessment of the quality of information provided by bank advisors regarding these elements.

The analysis examined the extent to which advisors were familiar with and able to provide information on the following aspects:

- the cost of maintaining the account (or information that it is unconditionally free),
- the cost of issuing a standard payment card (without custom graphics),
- conditions exempting the card fee (or information that the card is unconditionally free),
- information about the cost of withdrawals from foreign ATMs (or information that they are free),
- availability of the offer for children under 13.

The analysis enables us to evaluate the quality of service and, simultaneously, assess the knowledge of advisors, which may influence parents' decisions regarding financial products for their children.

The limited availability of banking services for children in many banks suggests a lack of offerings for children. Even having a reasonable offer is not a prerequisite for a bank's success. Banks that communicate costs and terms (e.g., fee waivers) build greater trust among customers. As can be seen, some advisors lack a thorough understanding of their bank's offerings. Employees from Santander and Bank Pekao stand out for their expertise.

There are also a few banks that lack many features for children. Expanding the availability of banking products for children in more banks can support the development of financial education from an early age. Standardizing cost communication and simplifying fee waiver policies would increase parents' trust in financial institutions.

Given that the offer becomes part of financial education, it should be simple and contain few complex terms. Children's financial education cannot be achieved by learning from their own mistakes, which often result from failing to read the terms and conditions of the fee and commission schedule.

Field research conducted in the United States suggests that one effective way for children to learn financial management is through experience managing a bank account (Collins, L'Esperance, Odders-White, 2018). Other studies have shown that having savings in childhood is associated with an increased likelihood of saving in adulthood (Brown, Taylor 2015).

This, therefore, represents a significant educational responsibility for bank management.

Based on the results of our survey, we believe that many banks should prioritize increasing training for advisors in the field of children's products.

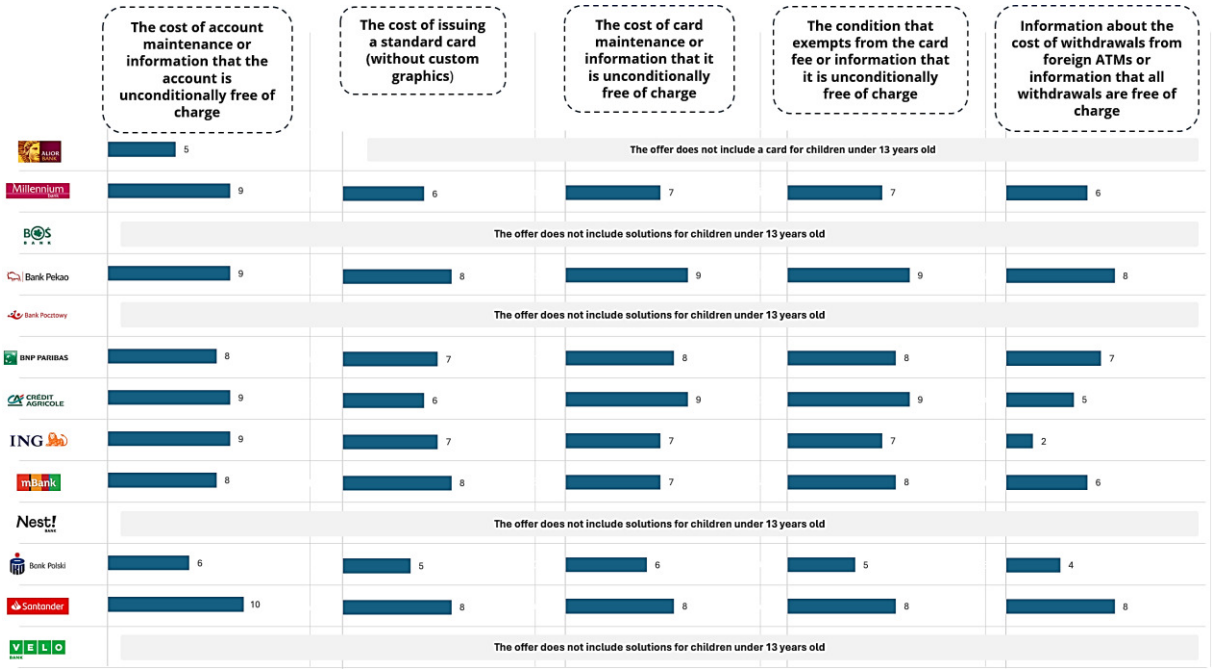


Figure 4. Information obtained about the basic parameters of the offer for children under 13 years old, provided without the customer asking (visit to the branch).

Source: Own study based on our own research during the 'Institution of the Year' project between 2022-2024.

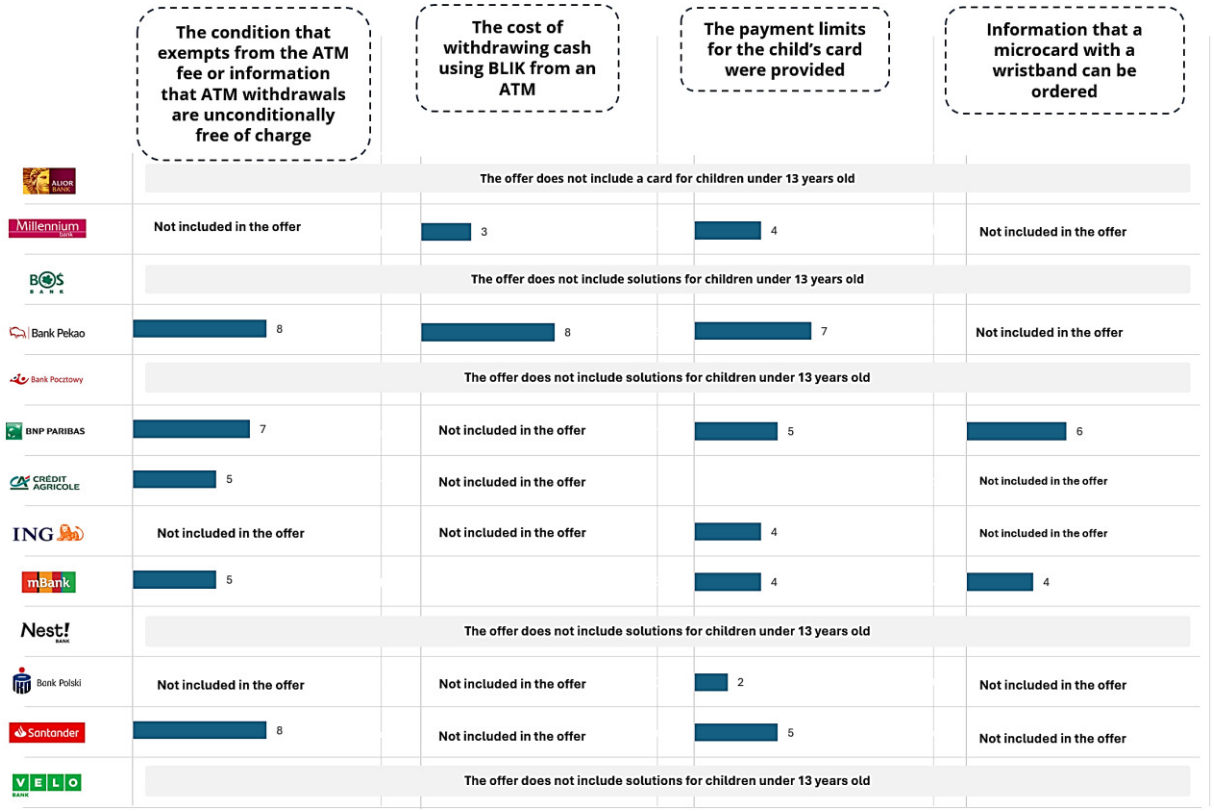


Figure 5. Additional information obtained about the parameters of the offer for children under 13 years old, provided without the customer asking (visit to the branch).

Source: Own study based on our own research during the 'Institution of the Year' project between 2022–2024.

Some parents expect their children to have access to similar features as adult customers, so some of these customers have higher expectations, which is confirmed by additional requirements (for example, regarding conditions for exemption from ATM fees, cash withdrawal fees, or the ability to order microcards with payment wristbands) (Figure 5).

The survey asked about several conditions regarding offers for children:

- conditions exempting ATM withdrawal fees or information that they are unconditionally free,
- the cost of withdrawing cash from an ATM using BLIK,
- information on card payment limits for children,
- the option to order a micro-card (e.g., in the form of a payment wristband).

The data shows significant differences in the level of knowledge of bank advisors, which may indicate:

- lack of standardized training,
- low priority given to children's accounts,
- varying approaches to products for children across different banks.

Even if a bank formally offers certain products, the lack of knowledge among advisors means that customers may not be fully informed about them, resulting in limited availability.

The analysis of the quality of the presentation of offers for children based on selected parameters allows for the formulation of several recommendations for bank management staff:

- investing in training advisors on children's products,
- standardizing offer communication across every available sales channel,
- internal monitoring of service quality for children's products.

Parents should ask directly about the availability of products for children, even if the advisor doesn't mention them themselves. Both charts reveal discrepancies not only in the banks' offerings themselves, but above all in the advisors' knowledge and the quality of communication with customers. Without remedial action, even the best formal offerings lose their impact if they aren't presented correctly.

As of the last survey (September 2024), some banks still didn't offer all the features expected by customers. The reasons for this may vary, from insufficient analysis of this customer group's needs to the complexity of the legal environment. Observing the systematic expansion of children's offerings at most banks over the three years of the survey, it can be assumed that the missing elements will be gradually introduced as customer interest grows.

4.3. Global study results

The research identified the best banks in terms of service quality for customers interested in opening a child's account.

Bank Pekao was the clear leader in service quality at bank branches, achieving a score of 93.3%. Santander Bank Polska came in second with a score of 87.6%, and ING Bank Śląski came in third with a score of 82.9%. According to the quality study guidelines (principles in Institution of the Year projects), an overall score of 80% or higher is considered satisfactory. This group of banks also included PKO Bank Polski, mBank, and Credit Agricole.

Only three banks fell below the 70% threshold. The results of the service quality study for customers interested in opening a child's account at a bank branch in each of the study periods are presented in Figure 6.

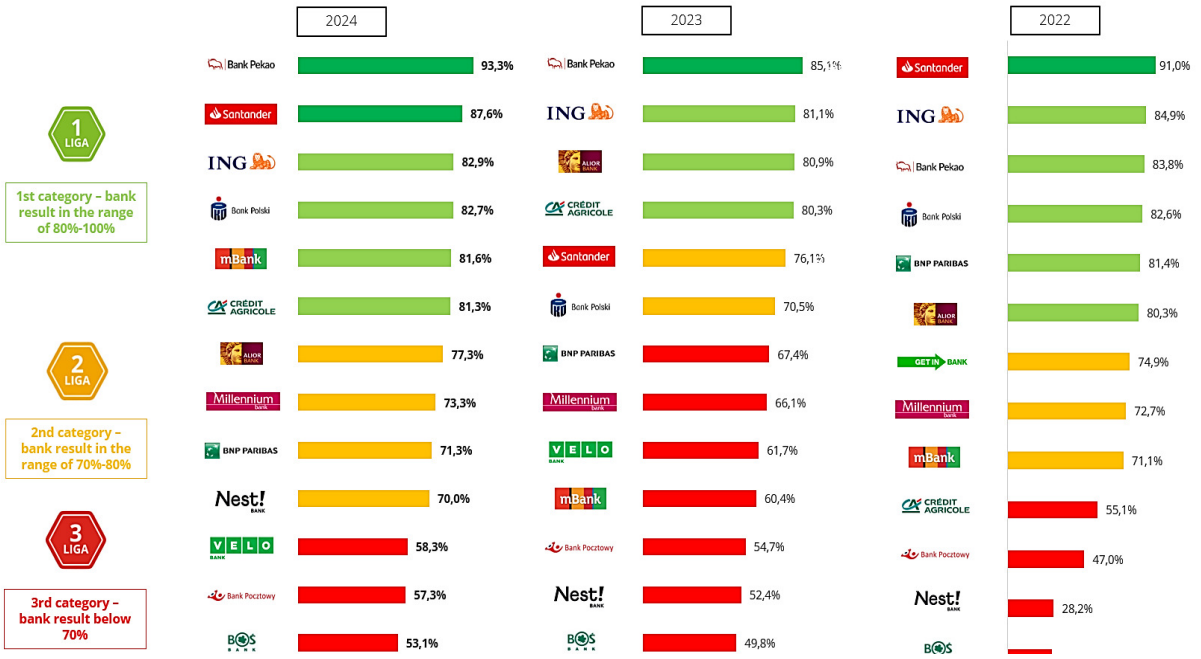


Figure 6. Global results of research on the quality of service for individuals interested in opening a children's account at a bank branch between 2022-2024.

Source: Own study based on our own research during the 'Institution of the Year' project between 2022-2024.

The results obtained in the first study, conducted in 2022 and initiating the investigation of children's accounts, revealed significant service quality deficiencies at seven banks. In the presented studies, the offers of individual banks were not evaluated and did not influence their results. The authors were curious to see how the potential of the banking offer would be utilized in customer contacts. Despite the lack of a comprehensive offer for the youngest age group, Santander Bank Polska's management was able to prepare its advisors qualitatively and impress customers by excellently presenting the offer for older children (over 13) and demonstrating useful functionalities for everyday use. At that time, Bank Pekao's management was one of only two banks able to offer a product that fully met customer expectations. Bank Pekao's advisors distinguished themselves primarily by their excellent preparation in terms of interview materials. Products for children were a crucial component of the banking offering. The availability of marketing materials, such as leaflets and other materials, significantly supported advisors and facilitated customer contact. In 2023, Bank Pekao became the clear

leader in bank branch service. In 2023, only nine banks offered services for children aged 7 to 13, and only seven banks provided children's cards, which were not always linked to the child's account.

In this respect, only Santander Bank Polska expanded its offerings in 2024. However, Bank Pekao and Bank Millennium offered the most options for children aged 7 to 13.

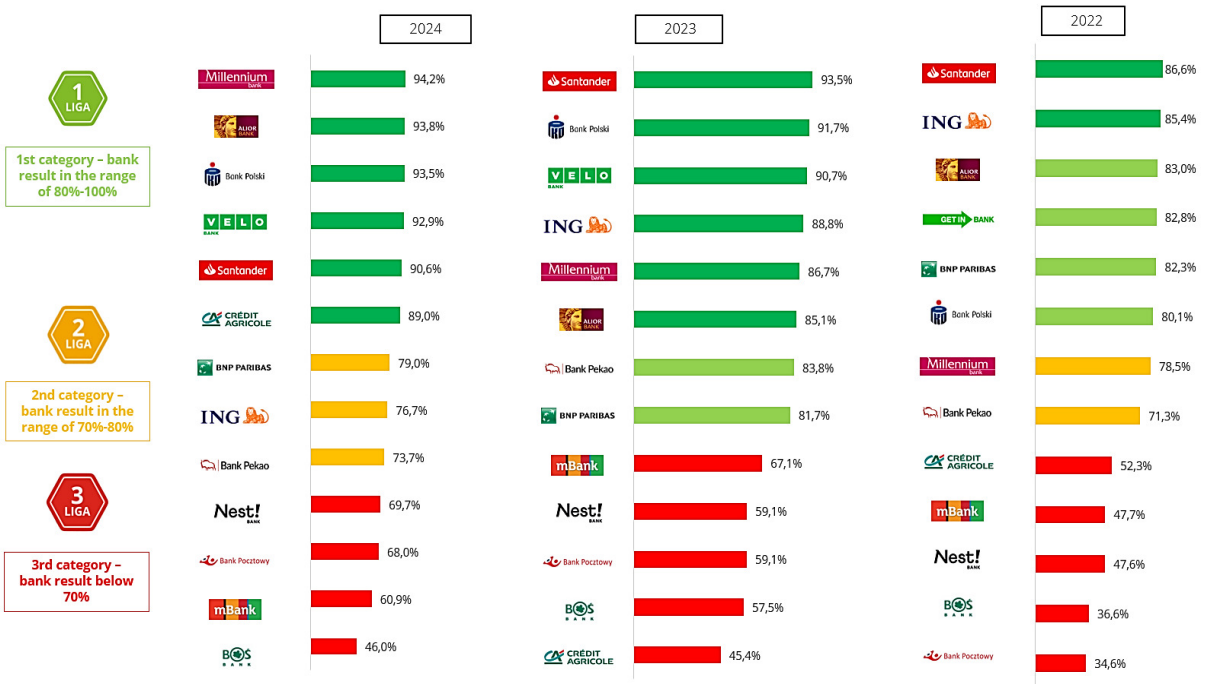


Figure 7. Global results of research on the quality of remote customer service for individuals interested in opening a children's account between 2022-2024.

Source: Own study based on our own research during the 'Institution of the Year' project between 2022-2024.

The results of the service quality survey for remote channels, targeting customers interested in opening a children's account, are presented in Figure 7 for the periods under study. Bank Millennium became the leader in remote communication, and as many as four banks did not meet expectations in this respect.

Other research conducted in Brazil shows that ensuring a consistent customer experience across both digital and traditional channels enables the building of stronger relationships, which in turn translate into increased engagement and long-term loyalty between the bank and its customers. A key element of building customer relationships is skillfully managing the customer experience across both channels (Gomes, Schmidt, 2024).

The study noted differences in customer service quality across different sales channels within the same bank. At Bank Pekao, where customers experienced excellent service quality in branches, the same offer on the hotline was presented at a significantly lower level (a score of only 56.9%). A similar difference occurred within the same bank at ING Bank Śląski, where the bank ranked third in terms of customer service quality in branch meetings, while it ranked second to last in hotline contacts. The opposite difference was observed at Bank Millennium,

Alior Bank, and Velobank, where hotline consultants provided good customer service; however, several areas requiring improvement were identified in the branches. A consistent level of service quality was observed across both channels at PKO Bank Polski and Credit Agricole. In the latter bank, in particular, a clear plan for discussing children's accounts was evident, which the consultants consistently implemented naturally.

Based on our research, an offer that fully meets customer needs offers better presentation opportunities, but is not the key to excellent service quality. The aforementioned cases of banks offering attractive deals that are poorly presented also confirm this. Service quality is rated poorly in one channel, while it is dramatically different in another, further confirming our conclusion. In such cases, it is necessary to implement a program to remedy the situation by diagnosing the cause and taking action. In such situations, banks can utilize patterns from other sales channels.

5. Summary

Based on the research, there has been a noticeable improvement in the quality of service provided to customers interested in opening accounts for their children over the three-year study period. Parents, when choosing a bank, are guided, among other factors, by the reliability of information provided by bank advisors regarding child-focused products and services. The ability to provide precise answers about a child's account and other related features directly impacts parents' trust and the final decision to choose a bank. Service quality is a significant factor in assessing the attractiveness of an offer. As the study shows, even the best-designed offer loses value if the advisor fails to present it correctly or is unaware of the details of its basic terms and conditions.

The lack of a unified approach across bank management to this customer group is detrimental, especially for customers who, in many cases, may be unaware that different banks offer completely different account features for children. Initially, the approach of banks and parents to child-focused offerings was primarily educational, but this has begun to change. Banks are starting to acquire customers at an early stage in their children's lives. It can be expected that account holders will develop strong brand loyalty and stay with them for years. Banks, therefore, treat such accounts as a long-term investment (Mianowana-Kubiak, 2014). This is an additional argument for a change in approach for banks that are not ranked in the first category by the Institution of the Year quality assessment assumptions.

The analysis was based on a selected group of the largest commercial banks in Poland; however, it has some limitations due to the exclusion of cooperative banks. However, considering the market share of the analyzed banks, the study allows for the generalization of results to the entire market. The research focused on a three-year time frame, and given the

dynamic changes in the banking sector, future conclusions may require updates in subsequent years. Another limitation is the relatively narrow scope of international literature, which makes it more difficult to compare the results with those of other countries.

In the future, it would be advisable to extend the analyses to a broader research sample encompassing the international market, although such an approach would require conducting studies outside Poland, for example, by a bank or another institution. Another direction of analysis could be to examine the long-term effects of customer loyalty acquired at an early age and the role of mobile technologies in building further relationships with clients.

Focus groups confirmed that offerings for the youngest customers are no longer just an educational tool; specific functionalities for children's accounts are also expected. A key factor in the perception of a bank's offerings is the quality of service across all sales channels. A well-tailored offering facilitates this task, but a lack of a proper approach to customer service, ultimately involving children, will prevent the customer from appreciating its appeal. This confirms the crucial importance of customer service quality for the sales success of any bank.

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WHY MANUFACTURING BACKFLOWS TO CENTRAL AND EASTERN EUROPE FAIL TO MATERIALIZE: INTRODUCING THE RESHORING READINESS LADDER (RRL)

Michał MŁODY[1*], Luciano FRATOCCHI[2]

[1] Poznań University of Economics and Business, Department of Strategic Management, Poznań, Poland; michal.mlody@ue.poznan.pl, ORCID: 0000-0001-5368-9719
[2] University of L'Aquila, Department of Industrial and Information Engineering and Economics, L'Aquila, Italy; luciano.fratocchi@univaq.it, ORCID: 0000-0001-9562-0744
* Correspondence author

Purpose: Despite COVID-19 disruptions and geopolitical tensions favoring supply chain regionalization, Central and Eastern Europe (CEE) has failed to capture anticipated manufacturing reshoring flows. This paper seeks to explain why and to introduce a conceptual framework identifying the binding constraints to reshoring in post-transition economies.
Design/methodology/approach: We analyze relocation cases from the Eurofound's European Restructuring Monitor (ERM) and develop a multi-theoretical framework - Reshoring Readiness Ladder (RRL), integrating transaction cost economics, the OLI paradigm, and global value chain governance.
Findings: Eurofound data reveal a critical paradox: while CEE attracts manufacturing relocations (intra-EMEA secondary relocations), none represent confirmed extra-EMEA-to-CEE nearshoring. This pattern reflects a "CEE capability trap" - the region is too developed for cost-based competition yet lacks ecosystem thickness for technology-intensive production.
Research limitations/implications: Our conceptual framework requires empirical validation across sectors and CEE countries. The RRL framework provides a foundation for future quantitative research on manufacturing location decisions.
Practical implications: Policy makers should abandon generic FDI attraction strategies and focus on building specialized ecosystems in narrow domains, while companies should consider staged relocation approaches co-locating engineering with production.
Originality/value: This paper introduces the RRL framework spanning four levels (institutions → capabilities → ecosystems → strategic positioning) and demonstrates that not only formal institutions but the broader ecosystem constitutes the binding constraint for CEE nearshoring success.
Keywords: reshoring, nearshoring, Central and Eastern Europe, Industry 4.0, global value chains.
Category of the paper: Conceptual paper.

1. Introduction

Despite EU integration, geographic proximity to Western markets and improving infrastructure, confirmed reshoring activities[i] to CEE remain limited, while companies mostly optimized logistics, inventories, and multi-sourcing (Młody, Fratocchi, 2022; Fratocchi et al., 2014b; Stępień, Młody, 2017). Although regionalization pressures (e.g. COVID-19, US–China decoupling, Russia-Ukraine war proximity) should have boosted extra EMEA-to-CEE nearshoring, hard evidence is weak. This paradox arises because CEE economies are too developed to sustain durable cost-based competition vis-à-vis Asian locations, yet too thin institutionally and ecosystem-wise - in terms of Industry 4.0 capabilities, dense supplier bases, and specialized services - to anchor nearshoring. We label this configuration the CEE capability trap, which explains why conventional push–pull logics fail to translate into relocations to CEE (Marcinkowska, 2017; Pluta-Zaremba et al., 2024), even if it seemed plausible that this region is natural post-transition reshoring destination[ii].

The paper pursues two linked aims: 1) to provide a systematic assessment of the scale and nature of manufacturing backflows to CEE, distinguishing between first-stage offshoring into the region and potential second-stage relocations; and 2) to develop a conceptual framework that helps explain the conditions under which reshoring to post-transition economies becomes feasible or constrained.

Our conceptual article offers a retrospective and critical reflection on the reshoring debate in CEE by revisiting the earlier predictions through a multi-level lens, combining transaction cost economics and the OLI paradigm with insights from dynamic capabilities, institutional theory, global value chain governance, and path dependence. We introduce the Reshoring Readiness Ladder (RRL) to explain why most CEE locations constitute binding constraints for reshoring. Incorporating institutional, strategic, and capability-based explanations - it seeks to identify structural barriers and contextual mismatches that limit CEE's attractiveness as a destination for reshored manufacturing.

The paper proceeds as follows. Section 2 situates our argument within the reshoring literature and outlines the theoretical lenses. Section 3 contrasts mid-2010s scenarios with subsequent European and CEE evidence and diagnoses ecosystem deficits, policy fragmentation, and strategic lock-ins. Section 4 presents the RRL, boundary conditions, and research avenues. Section 5 concludes with implications for policy and managerial practice.

2. Theoretical background

As classic models predict increasing international commitment with learning (e.g., Uppsala), companies progressively deepen international commitment based on accumulated knowledge and environmental adaptation (Figueira-de-Lemos et al., 2011). Yet empirical evidence increasingly challenges this linear progression. Internationalization often exhibits intermittency rather than persistence (Bernini, Du, Love, 2016), with frequent instances of 'foreign exit' - reductions in international equity or export volumes (Cefis et al., 2022). This reversal phenomenon aligns with Benito and Welch's (1997, p. 9) concept of 'de-internationalization': any action reducing cross-border engagement. Manifestations include international divestments (Boddewyn, Torneden, 1973) and various reshoring configurations - back-shoring to home countries, near-shoring to home regions, or further off-shoring to alternative locations (Fratocchi et al., 2014). These reconfiguration strategies gain prominence as deglobalization (Garg, Sushil, 2018), de-internationalization (da Fonseca, da Rocha, 2022) decoupling (Witt et al., 2023), and regionalization (Enderwick, Buckley, 2020) reshape international business discourse. UNCTAD's (2020b) projection of four alternative trajectories - diversification, replication, reshoring, and regionalization - directly addresses these shifts. The regionalization scenario, involving what Barbieri et al. (2019) term 'second-degree relocations' through nearshoring, theoretically positions CEE as natural destination for Western European production previously offshored to Asia. Yet as our empirical analysis demonstrates (presented in next section), this theoretical potential remains unrealized.

Over the past two decades, the global manufacturing landscape has undergone a significant reconfiguration as companies increasingly reassess offshoring and consider reshoring options (Li et al., 2024; Vanchan et al., 2018). This turn - catalyzed by shifting market requirements, technological advances and shocks such as COVID-19 and geopolitical risk - should be read not as a simple correction of past location choices, but as a broader reconsideration of how production networks are conceived and governed (Nölke, 2022; Pegoraro et al., 2025), with implications for reindustrialization and sustainability in home economies (Di Stefano et al., 2024; Pylypenko, Herasymenko, 2022). Multi-theory approaches now consider environmental and social criteria alongside economics, challenging cost-centric models and linking relocations to policy regimes, regulatory predictability and political stability (McIvor et al., 2022; Di Stefano et al., 2024; Srai, Ané, 2016; Kwon, Hwang, 2023). Empirically, reshoring reflects a dual mechanism: push factors in host locations (e.g. rising wages, political risk, IP concerns, disruption) and pull factors at home (e.g. automation/Industry 4.0, skills, supportive policy) (Kim, Chung, 2022; Kwon, Hwang, 2023). Industry 4.0 narrows labor-cost differentials and increases the value of proximity to design, markets and innovation ecosystems (Stentoft et al., 2024).

The theoretical foundations of reshoring evolved from single-lens explanations to multi-theoretical accounts combining transaction cost economics, the OLI paradigm, and dynamic capabilities (Williamson, 1981; Dunning, 1980; Teece et al., 1997). Recent syntheses emphasize complementarities among efficiency, market, and strategic-asset motives (Fratocchi et al., 2016). Extensions highlight institutional voids that persist despite formal integration (Khanna, Palepu, 2000) and global value chain governance showing how lead-company power constrains reversibility (Gereffi et al., 2005). These lenses are particularly salient in post-transition economies (Götz, Jankowska 2022). Where institutional development is uneven, supplier bases fragmented, and innovation systems immature, the theoretical logic for reshoring may not readily translate into practical feasibility. A comprehensive framework must therefore combine institutional theory (North, 1990) with the notion of capability voids and acknowledge strategic ambiguity in policy and corporate communication when diagnosing why reshoring may be attractive in theory yet unattainable in practice.

Despite advances, gaps persist. Much of the literature still privileges single lenses, exploratory/case designs with limited generalizability, developed-economy sectors, inconsistent definitions and a lack of longitudinal evidence (Li et al., 2024; Bornert, Musolino, 2024; Pegoraro et al., 2025; Siddiqui et al., 2024). This motivates a more contingent theorization that integrates heterogeneity, industry specifics and evolving sources of advantage, and that recognizes qualitative motives alongside economic calculus (Fratocchi et al., 2016). In the CEE context, however, mainstream assumptions of reversibility are problematic: deteriorating Asian conditions plus improved home capabilities have not yielded broad relocations. Drawing on semi-periphery theory and dependent market economies, we posit that CEE is simultaneously too developed for durable cost competition and too thin institutionally and ecosystem-wise for capability-led reshoring.

3. Why reshoring did not happen in CEE: from scenarios to structural, institutional and strategic barriers

Mid-2010s reshoring scenario assessments for WE and CEE envisaged three broad pathways, back-reshoring to Western home countries, near-reshoring to CEE, and further offshoring to lower-cost locations (e.g., Młody, 2016). Those scenarios primarily considered reshoring by Western European lead companies rather than by CEE companies, as these projections anticipated that CEE would capture meaningful reshoring flows as companies balanced cost and market access. The subsequent divergence between prediction and reality requires a deeper diagnosis of why relocations did not materialize on a scale and how this gap maps onto three interlocking barrier sets.

Previous assumptions proved problematic. First, assessments overestimated manufacturing ecosystem fungibility, treating locations as substitutable based on factor costs while underweighting ecosystem depth and embedded capabilities (Sturgeon et al., 2008). Second, they under-valued capability hierarchies in GVCs: market forces alone were expected to move CEE from assembly to comprehensive manufacturing, whereas GVC governance often produces functional lock-ins that limit the mandates of subordinate partners (Gereffi, Humphrey, Sturgeon, 2005; Ponte, Sturgeon, 2014). Third, they misread policy readiness, implicitly presuming the "embedded autonomy" needed to devise and sustain long-horizon industrial strategies - capacity that remains uneven in post-transition settings (Evans, 1995; Bohle, Greskovits, 2012). This amounts to a misspecification: CEE's theoretical potential (proximity, EU membership, educated workforce) has not translated into practical readiness (in terms of ecosystem depth, innovation capacity, strategic autonomy) (Plank, Staritz, 2013). The pattern aligns with the dependent market economy thesis, whereby formal integration masks persistent capability deficits and constrained strategic agency (Nölke, Vliegenthart, 2009).

Our evidence draws on relocation decisions recorded in Eurofound's European Restructuring Monitor (ERM), covering cases announced and/or implemented between 2002-2024. We restrict the sample to manufacturing and classify each observation as first-stage offshoring and second-stage relocation (based on the origin–destination pair and company footprint prior to the move)[iii]. Eurofound's comprehensive database (Table 1) reveals patterns fundamentally contradicting regionalization scenarios. The data reveal a critical pattern: while the database records some nearshoring cases overall, after disaggregation and cleaning, we find no confirmed extra-EMEA-to-CEE nearshoring cases in ERM. The cleaning process involved excluding cases where companies merely expanded existing CEE operations, distinguishing genuine relocations from Asia from intra-European movements.

Table 1.

Manufacturing relocation patterns by destination and type[iv]

Relocation decision	EE increase	EE reduction	Intra EE	Intra WE	n.c.	WE increase	WE reduction	Total
Backshoring	3	16	2	73	-	8	27	129
Further offshoring	2	27	-	-	-	1	124	154
Nearshoring	-	6	-	-	-	2	35	43
Offshoring	708	16	36	106	8	34	155	1063
RTC	284	19	63	139	24	1	29	559
Total	997	84	101	318	32	46	370	1948

Source: Analysis of Eurofound data, authors' calculations.

Table 2 shows 708 first-stage offshoring cases (543 intra-EMEA + 165 extra-EMEA) and indicates that CEE captures initial offshoring rather than second-stage returns from distant locations. Table 2 is a drill-down of the EE-increase bucket from Table 1, disaggregating first- vs second-stage flows.

Table 2.
Detailed relocation flows to Eastern Europe by stage and origin

Relocation decision	Stage	EE increase
I step relocation:		
Offshoring Intra EMEA	First	543
Offshoring from Extra EMEA	First	165
II step relocation:		
RTC intra EMEA	Second	284
Backshoring intra EMEA	Second	3
Further offshoring from Extra EMEA	Second	2
Total		997

Source: Analysis of Eurofound data, authors' calculations.

This pattern - lack of genuine extra EMEA/Asia-to-CEE nearshoring (as indicated in table 1) - directly contradicts both academic predictions (Młody, 2016), UNCTAD's (2020) regionalization scenario and policy expectations following COVID-19 supply chain disruptions. CEE attracts first-stage offshoring but fails to capture second-stage nearshoring from distant locations. The 284 RTC cases require careful interpretation - these represent secondary relocations within the EMEA region - companies already operating in one EMEA country moving to another. However, detailed analysis suggests these are predominantly moves of Western European headquartered companies from higher-cost CEE countries to lower-cost ones, rather than the anticipated Asia-to-CEE nearshoring flows.

The CEE capability trap translates into three interlocking barriers that explain why Asia-to-CEE nearshoring failed to materialize. These barriers concern: (1) the technology-ecosystem gap undermining productivity gains, (2) institutional fragmentation reducing investor confidence, and (3) strategic lock-ins within global value chains that constrain functional upgrading. We discuss each barrier in turn.

At the core is a technology-ecosystem gap: robot density in major CEE economies remains far below WE benchmarks, and adoption of advanced Industry 4.0 is markedly lower (IFR, 2023). Technology deficit directly undermines any productivity gains that could offset CEE's higher labor costs relative to Asia (Szalavetz, 2019; Éltető 2019). Moreover, thin supplier bases and scarce specialized services (tooling, testing, certification) limit just-in-time orchestration, even in ostensibly strong sectors like automotive (Pavlínek, 2018, 2020; Bečicová, Blažek, 2015). The development of Industry 4.0 technologies - including automation, robotics, digital twins, and artificial intelligence - may render reshoring economically viable, as automation and digitalization reduce the importance of low labor costs and enhance supply chain resilience (Yaqub, Alsabban, 2023). Literature reviews indicate that these technologies enable more flexible and integrated production management, thereby increasing the attractiveness of locations closer to end markets (Farboodi et al., 2024). Although a meta-analysis of empirical studies shows mixed effects of automation on reshoring decisions (Pinheiro et al., 2023), specific implementations of Industry 4.0 technologies report significant operational gains (e.g. reduction in cycle time, decrease in defect rates) which indirectly support the economic rationale for reshoring (Damasceno et al., 2024).

These ecosystem weaknesses are further amplified by institutional fragmentation that undermines investor confidence. Although formal institutions exist across CEE, their quality and predictability fall short of requirements for long-horizon manufacturing investments. Electoral cycles drive frequent policy revisions that elevate perceived risk, preventing the stable industrial strategies necessary for complex manufacturing to take root (North, 1990; Bohle, Greskovits, 2012). Inconsistent regulatory enforcement and lengthy administrative timelines increase compliance costs for technology-intensive activities (Kwon, Hwang, 2023).

Compounding these structural and institutional barriers, strategic lock-ins prevent the transformative changes necessary for reshoring. Companies facing shifting global costs increasingly pursue incremental optimization through automation, multi-sourcing, and inventory buffers rather than fundamental footprint reconfiguration (Cohen et al., 2017). Global value chain governance reinforces this inertia as buyer-driven chains and capability hierarchies constrain subsidiary mandates, creating functional lock-ins that prevent upgrading beyond assigned roles (Gereffi, Humphrey, Sturgeon, 2005; Ponte, Sturgeon, 2014).

These three barriers converge to reinforce the CEE trap. The trap's economic dimension manifests in an untenable positioning: manufacturing labor costs are much below Western European levels, seemingly attractive for nearshoring. Yet these same costs exceed Asian benchmarks (e.g., Vietnam, Bangladesh) (Eurostat, 2024; European Commission, 2025). This intermediate position creates a "valley" where CEE is simultaneously too expensive for pure labor-cost arbitrage from Asia while lacking the Industry 4.0 capabilities and ecosystem density necessary for productivity-based competition with Western Europe. Without advanced automation to offset wage differentials, stable institutions to attract patient capital, or strategic reorientation toward capability building, the region remains locked in the CEE capability trap - a self-perpetuating cycle where incremental adjustments substitute for the transformative relocations that regionalization pressures should theoretically produce.

4. Toward a post-transition theoretical lens: the Reshoring Readiness Ladder (RRL)

Three decades after the socialist-to-market transition, CEE economies face a paradox that mainstream frameworks struggle to explain. While transition economics anticipated convergence through liberalization and institutional reform (Kornai, 2006), the reshoring experience reveals that formal EU integration and substantial FDI have not automatically produced the capability depth required for Industry 4.0-intensive manufacturing. The dependent market economy thesis (Nölke, Vliegenthart, 2009) helps explain this persistence but offers limited guidance on escaping subordinate value-chain roles.

The empirical patterns demand reconceptualization. We propose the Reshoring Readiness Ladder (RRL) - a framework explaining structural barriers to regionalization in post-transition economies. Our framework differs from existing readiness assessments (e.g. OECD FDI Restrictiveness Index) by capturing dynamic capability accumulation rather than static institutional metrics.

Building on the barriers identified in the previous section, we conceptualize Reshoring Readiness as an emergent property arising from the interaction of four progressive dimensions: institutions (I), capabilities (C), ecosystems (E), and strategic positioning (S). Rather than viewing these as independent factors, we see them as interconnected layers that build upon each other, creating a developmental ladder from basic market functioning to innovation leadership.

Level 1 - institutional foundations (I) establish the essential preconditions for any modern manufacturing operation. Most CEE EU members formally comply with Level 1 requirements in terms of legal frameworks and macroeconomic stability. However, formal compliance does not automatically translate into *effective credibility*. Investors perceive high volatility due to frequent policy shifts, selective enforcement, and unpredictable administrative practices. Thus, while L1 foundations are legally in place, their credibility remains fragile, reducing the long-horizon certainty needed for complex manufacturing investment. In this sense, CEE countries are *formally at Level 1* but often *functionally below the effective threshold* of L1 maturity.

Level 2 - capability building (C) emerges when locations move beyond routine assembly toward more complex operations. This transition requires technical education systems aligned with automation needs, local suppliers progressing from build-to-print to build-to-spec manufacturing, and rising company-level absorptive capacity for new technologies (Cohen, Levinthal, 1990; Szalavetz, 2019). This level responds to the skills and absorptive-capacity gaps identified among structural ecosystem deficits (e.g. selected automotive clusters in CEE demonstrate partial Level 2 characteristics).

Level 3 - ecosystem development (E) materializes when dense networks of specialized capabilities create self-reinforcing advantages that transcend individual company efforts. Mature ecosystems feature specialized service providers for tooling, testing, and certification and active university-industry collaboration generating joint intellectual property (Porter, 1998; Etzkowitz, Leydesdorff, 2000). This level directly addresses the structural ecosystem thinness that constrains CEE's reshoring potential.

Level 4 - strategic positioning (S) represents the apex where locations shape global industry standards rather than merely participating in established value chains. These regions host lead companies that orchestrate global production networks, repeatedly introduce innovations that reset industry benchmarks, and possess distinctive specializations recognized worldwide (Gereffi et al., 2005). This level transcends the strategic inertia and cognitive lock-ins discussed in Section 3, requiring locations to define rather than follow industry trajectories. Probably no CEE location has achieved comprehensive Level 4 status (benchmark regions like Baden-Württemberg in automotive).

The progression is non-linear: achieving Level 2 does not guarantee Level 3 emergence, as ecosystem development requires critical mass effects that policy alone cannot generate. The relationship between these levels and our earlier analysis of barriers reveals why CEE struggles with reshoring. Institutional ambiguity undermines Level 1 stability, capability gaps prevent solid Level 2 achievement, ecosystem thinness blocks Level 3 emergence and strategic inertia preclude Level 4 aspirations. To diagnose where specific locations stand, we identify observable signatures for each level (Fig. 1).

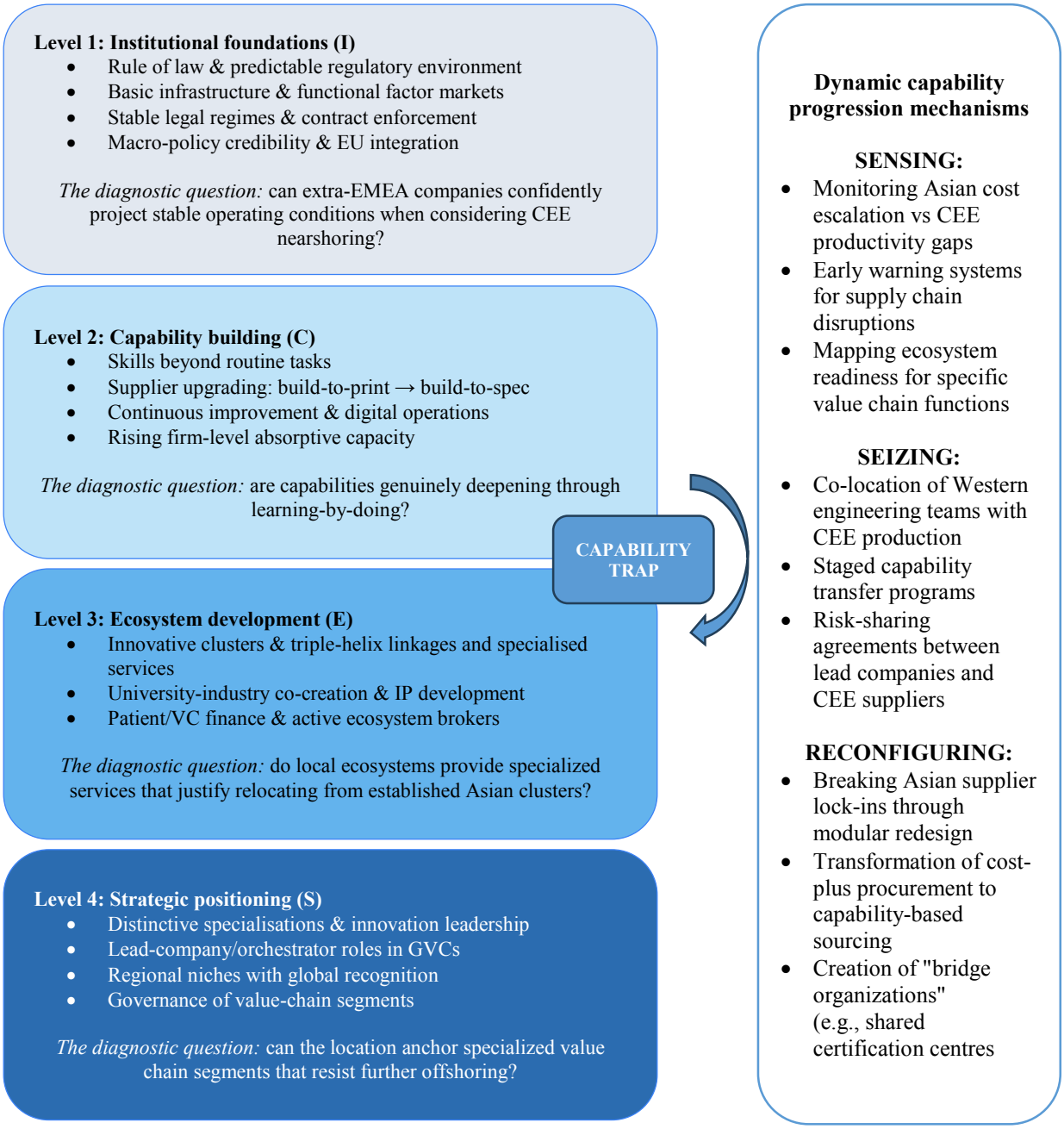


Figure 1. The Reshoring Readiness Ladder (RRL).

Source: own elaboration.

Understanding how locations advance between levels requires examining both the mechanisms enabling progression and the contextual factors shaping their effectiveness. Drawing on dynamic capabilities theory (Teece et al., 1997), we identify three interconnected processes driving upward movement: sensing, seizing and reconfiguring.

Sensing involves systematically recognizing opportunities and threats through strategic intelligence gathering: industry foresight exercises anticipating technological shifts, lead-company road mapping aligning supplier development with future needs, and monitoring global best practices. Effective sensing prevents locations from being blindsided while identifying capability development windows. Seizing requires mobilizing resources to capture opportunities before windows close: forming coalitions that combine patient capital with coordinated training, using mission-oriented procurement to stimulate capability development, and creating demonstration projects that prove feasibility to skeptics. Successful seizing often requires overcoming coordination failures that plague fragmented institutional environments. Reconfiguring enables locations to abandon obsolete practices and build new advantages through institutional learning that improves policy design, company-level unlearning of cost-only competition models, and ecosystem brokers that facilitate knowledge flows between otherwise disconnected actors.

These mechanisms, however, operate on fundamentally different timescales, creating the temporal trap identified earlier. Companies make location decisions on few year horizons, political cycles rarely exceed 4-5 years (Zhao et al., 2023), yet ecosystem development unfolds over decades (Salamatov et al., 2021). This mismatch explains why policy interventions often disappoint: they promise transformation on political timescales but deliver results on evolutionary ones. Extended timescales underscore why short-term policy horizons prove particularly problematic.

The ladder's application may vary significantly across contexts, making boundary conditions essential to specify. Besides, geographic heterogeneity within CEE suggests selective rather than uniform upgrading metropolitan clusters with existing strengths show greater L2→L3 progression potential than peripheral regions starting from scratch. Path dependence creates both opportunities and constraints-regions specialized in assembly face substantial switching costs when attempting functional upgrading, as established competencies and mental models resist change (Pavlínek, 2020; Martin, Sunley, 2006). This reinforces the value chain subordination lock-in identified by Grodzicki & Geodecki (2016), whereby integration as efficient assemblers paradoxically constrains advancement. Building on this framework, we advance three propositions connecting theoretical development to testable empirical claims, followed by our framework's contributions to existing theory.

1) In post-transition economies with basic institutional foundations (L1), ecosystem thickness (L3) rather than institutional quality constitutes the primary barrier to advanced manufacturing attraction (binding constraint).

2) Manufacturing reshoring probability increases when multinational companies co-locate R&D facilities with production (engineering co-location).
3) Regions achieving L3 readiness in narrow specializations demonstrate higher reshoring success rates than those pursuing broad-based upgrading strategies (specialization advantage).

These propositions require empirical validation across sectors, periods, and contexts, suggesting research designs ranging from matched comparisons to event-history analyses. The RRL framework advances reshoring literature through several contributions. First, it synthesizes dynamic capabilities with the literature on institutional voids (Khanna, Palepu, 2000; Szalavetz, 2019) to explain development under partial institutional conditions - formal institutions alone are insufficient without complementary informal institutions and intermediaries that emerge through repeated interaction. Second, by incorporating global value chain governance (Gereffi et al., 2005; Ponte, Sturgeon, 2014), the framework highlights how positional constraints hinder functional upgrading within existing chains proves harder than developing new specializations, as governance structures resist role redefinition, reinforcing value chain subordination (Grodzicki, Geodecki, 2016). Third, drawing on economic geography insights on cluster stickiness (Martin, Sunley, 2006) and institutional thickness, it explains why established locations retain advantages despite cost convergence. By identifying concrete progression pathways, the framework offers cautious optimism, suggesting that successful CEE reshoring (mainly nearshoring) requires more than correcting market failures. In this way proposed framework the offers analytical clarity and practical guidance for sustained upgrading.

5. Conclusions and implications

Our multi-level analysis reveals that CEE's failure to capture nearshoring flows despite regionalization pressures is not a failure of policy but a structural paradox. Policy volatility matters, but without ecosystem depth even stable regimes won't attract complex relocations. The RRL framework replaces generic attraction narratives with structured progression. Most CEE economies have not reached the ecosystem maturity (L3) where complex relocations become both viable and repeatable. The promise of proximity will transform into production reality in CEE only when patient policy meets pragmatic business strategy on the long climb toward capability maturity. Until then, the region's manufacturing renaissance remains an aspiration waiting for its foundation. For nearshoring specifically, CEE countries must abandon generic attraction strategies and focus on building specialized ecosystems in narrow domains where they can achieve Level 3 readiness. Our RRL framework contributes to reshoring theory by (1) moving beyond binary push-pull models to multi-level readiness

assessment, (2) identifying ecosystem thickness rather than institutional quality as the binding constraint in post-transition economies, and (3) explaining why proximity and formal integration fail to generate expected nearshoring flows.

Policy implications

Four priorities emerge. First, simplify and stabilize the policy landscape - reduce the number of instruments, specify clear service standards, and guarantee continuity across political cycles. Second, invest in connective infrastructure - technical systems and institutional support. Third, link incentives to measurable capability gains - support should reward suppliers who graduate from build-to-print to build-to-spec. Fourth, extend time horizons through mission-oriented programs - multi-year procurement commitments can create the patient capital that ecosystem development requires. The EU holds a unique lever: cross-border ecosystem integration. Besides, existing EU instruments could support RRL progression through various mechanisms, e.g. Digital Innovation Hubs for technology transfer, Horizon Europe's Widening Actions for capability building in peripheral regions, the European Chips Act for mission-oriented ecosystem development, and Recovery and Resilience Facility funds for strategic infrastructure investments (European Commission, 2021-2023).

Managerial implications

The RRL suggests practical strategies that preserve future options while reducing risk. The first approach involves designing for staged relocation. By modularizing products and processes, complexity can migrate in manageable waves. During this phase, the company runs intensive supplier-development programs focused on changeover efficiency and yield improvement. Only after suppliers demonstrate specific capabilities do motor and control systems follow. This transforms reshoring from a single decision into a sequence of measured steps. The second approach requires co-locating engineering talent with production. Procurement contracts should reflect this logic, rewarding capability development alongside cost reduction through shared improvement gains and milestone-based commitments. CEE suppliers pursuing upgrades should specialize deeply in narrow capabilities and demonstrate progress through verifiable metrics.

Limitations and avenues for future research

Our conceptual framework requires empirical validation - we proposed diagnostic signatures for each RRL level but avoided numerical scoring to prevent false precision. Besides, we acknowledge that our analysis treats CEE as relatively homogeneous, while significant sub-regional and sectoral diversity exists across the region. Advanced manufacturing clusters in the Czech Republic or Western Poland demonstrate different readiness levels than peripheral areas in Romania or Bulgaria. Future applications of the RRL framework should account for this

heterogeneity through differentiated sectoral and sub-regional analyses. Additionally, the temporal scope may be insufficient to capture delayed reshoring responses to recent geopolitical disruptions (post-2019). Three research priorities stand out. First, researchers should develop practical diagnostic tools - combining structured interviews, document analysis, and observable indicators. Second, proposed hypothesis needs empirical testing. Do investments in technical infrastructure and intermediaries generate better outcomes in terms of reshoring examples than generic institutional improvements once basics are satisfied? Does co-locating engineering with production measurably increase relocation probability after accounting for costs? Matched comparisons and event-history analyses offer feasible approaches. Third, the temporal dimension deserves focused attention. Which policy instruments successfully extend planning horizons beyond electoral cycles? How do government initiatives interact with company-level sequencing strategies? Understanding these dynamics could reveal how incremental gains compound into ecosystem transformation rather than dissipating with each political transition.

The reshoring paradox in CEE reveals fundamental misalignments between theoretical potential and practical readiness. Our analysis demonstrates that successful manufacturing relocation requires more than geographic proximity or cost advantages - it demands ecosystem maturity, institutional stability, and strategic vision operating on generational timescales. The RRL framework provides both diagnostic tools and development pathways, but its implementation requires patience and sustained commitment beyond typical policy cycles. As global value chains continue to reconfigure, CEE's ability to capture reshoring flows will depend not on competing for yesterday's advantages but on building tomorrow's capabilities. The journey from peripheral assembly platform to integrated manufacturing hub remains challenging, yet the framework presented here offers a roadmap for those willing to undertake this transformation.

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Footnotes

[i] Reshoring is an umbrella term for the return of previously offshored activities. It includes both back-reshoring (relocation to the company's home country) and nearshoring (relocation to a geographically closer third country). The literature also recognizes further offshoring (to another low-cost location) and relocation to a third country - RTC within the same macro-region (Fratocchi et al., 2014; Barbieri et al., 2019).

[ii] We distinguish between "post-transition" - referring to CEE's completed institutional transformation from planned to market economies - and "semi-peripheral" - denoting the region's intermediate structural position in global value chains between core economies (controlling technology and capital) and peripheries (providing basic inputs). CEE has achieved post-transition status through EU integration and market reforms yet remains semi-peripheral in its functional specialization as an assembly platform. This dual characterization may explain why formal institutional convergence has not translated into the deep capabilities required for Industry 4.0-intensive reshoring.

[iii] Manufacturing (NACE C) cases from ERM (2002-2024); ERM events are derived from media-sourced narratives. Under our coding scheme, we identify no unambiguous cases of extra-EMEA-to-CEE nearshoring duplicates removed. ERM entries do not always allow a full reconstruction of prior locations in second-stage relocations, so such flows may be underestimated. RTC = Relocation to a Third Country (secondary relocation within EMEA).

[iv] Definitions: WE = Western Europe; EE = Eastern Europe/CEE; n.c. = not classified; Backshoring = relocating production to the home country; *Nearshoring* = relocating to a third country within the home region (e.g., company from CEE / Western Europe → China → CEE); *Offshoring* = relocating to a distant region (e.g., Western Europe → Asia or CEE); *RTC (Relocation to a Third Country)* = second-stage relocation within EMEA (e.g., WE → CEE or CEE → CEE).

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NEGATIVE ELECTRICITY PRICES IN POLAND IN THE CONTEXT OF VALUE ADDED TAX (VAT)

Wojciech NARUĆ

Institute of Economics and Finance, University of Szczecin; wojciech.naruc@usz.edu.pl,
ORCID: 0000-0002-6932-5933

Purpose: The purpose of this article is to examine the VAT implications of negative electricity prices in Poland. This phenomenon, increasingly observed on the Polish Power Exchange (TGE), gives rise to interpretative challenges due to the absence of explicit statutory provisions. The article is addressed to academics, policymakers, and energy sector practitioners.
Design/methodology/approach: The study applies a combination of legal-dogmatic analysis, case study methodology, and empirical examination of hourly Day-Ahead Market (RDN) prices for the period from 2023 to mid-2025. It draws on EU and Polish legislation, case law of the CJEU and national courts, as well as more than thirty tax rulings issued by the National Tax Information Office.
Findings: In the course of the research, the research established that there is interpretative divergence regarding the classification of transactions concluded at negative prices – whether they should be treated as a supply of goods or as a taxable service. Tax rulings and court judgments increasingly adopt the view that negative-price settlements constitute services rendered by the purchaser to the seller. Furthermore, the study demonstrates a marked increase in both the frequency and the magnitude of negative prices in Poland. The broader economic, operational, and fiscal implications of these findings are discussed in detail in the Discussion section.
Research limitations/implications: The scope of the research is limited to the Polish electricity market and does not include a comparative analysis of other EU jurisdictions.
Practical implications: Clarification of VAT rules would mitigate legal uncertainty, enable more accurate settlements, and reduce the risk of tax disputes. Clearer guidance could also strengthen the financial stability of renewable energy projects exposed to price cannibalisation.
Social implications: Greater predictability in VAT treatment may indirectly support the energy transition and climate policy objectives by encouraging investments in renewable energy and storage technologies, thereby enhancing public trust in regulatory frameworks.
Originality/value: This article provides a comprehensive interdisciplinary analysis of the VAT consequences of negative electricity prices in Poland, combining empirical market data with legal-dogmatic and case study approaches.
Keywords: negative electricity prices, value added tax (VAT), electricity market, renewable energy sources, Poland.
Category of the paper: Research paper, case study.

1. Introduction

In recent years, the Polish electricity market has increasingly experienced the phenomenon of negative electricity prices. The rising share of renewable energy sources (RES) in the energy mix – relative to conventional generation sources – combined with limited demand-side flexibility and intensifying climate change, has contributed to greater price volatility across European Union (EU) member states. Under specific conditions of electricity oversupply, prices may fall below zero, which means that energy suppliers are forced to pay consumers for withdrawing electricity from the grid. Although initially marginal, this phenomenon has acquired significant practical relevance, particularly in the context of tax law, and most notably with respect to value added tax (VAT).

The aim of this article is to analyse the VAT implications of negative electricity prices in Poland. This problem, increasingly observed on the Day-Ahead Market (RDN) of the Polish Power Exchange (TGE), generates a number of practical and interpretative challenges stemming from the absence of explicit statutory provisions and the necessity of applying the general principles governing the taxation of supplies of goods and the provision of services.

The originality of this article lies in its comprehensive interdisciplinary approach, which combines empirical analysis of Polish Day-Ahead Market data (2023-2025) with a legal-dogmatic study of EU and national VAT law, administrative court rulings, and more than thirty tax interpretations. This integrated perspective provides new insights into the fiscal and legal consequences of negative electricity prices in Poland.

The study adopts a qualitative and interdisciplinary approach, combining the method of legal-dogmatic analysis with case study methodology. The legal-dogmatic analysis covers the provisions of Council Directive 2006/112/EC (Council Directive, 2006) on the common system of value added tax, the Polish Act of 11 March 2004 on Value Added Tax (VAT Act, 2004), as well as the jurisprudence of the Court of Justice of the European Union (CJEU), Polish administrative courts, and individual tax rulings issued by the Director of the National Tax Information Office. The study also draws on market data for 2023–2024 and the first half of 2025, together with tax rulings issued by the National Revenue Administration, and includes a comparative assessment of practices and solutions implemented in selected EU member states. The case study examines concrete instances of negative electricity prices in Poland and other EU jurisdictions, using hourly and daily spot market data – including that of TGE – reports of transmission system operators, publications of independent analytical centres, official documents and government reports, as well as industry literature and expert studies. This methodological framework has made it possible to combine theoretical analysis with empirical observations of electricity market operations, thereby enabling the formulation of precise legislative and interpretative recommendations.

2. Literature Review

The phenomenon of negative electricity prices in European markets has been increasingly examined in academic literature and industry reports. According to Eurelectric (Eurelectric, 2024), negative prices are becoming more frequent in the short term – particularly during periods of low demand and favourable conditions for renewable energy generation – which underscores the critical role of system inflexibility and limitations in energy storage. Market analyses further confirm that the development of energy storage constitutes a key factor that may reduce the occurrence of negative prices in the future (ICIS, 2024). The mechanisms leading to prices falling below zero have also been analysed by Reichenberg, Hirth and Söder (Reichenberg et al., 2021), who describe the so-called price cannibalisation effect, i.e. the decline in the profitability of RES investments during peak production hours, resulting in negative spot market prices. Consequently, electricity markets exhibit a tendency towards a decreasing market value of renewable generation as installed capacity expands.

In the Polish context, these processes are amplified by the dynamic development of renewable energy, the implementation of the net-billing system, and the limited flexibility of the electricity market. Nagaj (Nagaj, 2014) notes that despite the formal liberalisation of the market, the significant role of the state – through regulatory and fiscal instruments – remains one of the key factors shaping the environment of the Polish power sector. Industry articles (Gramwzielone, 2023; Nomad Electric, 2024; Elżbieciak, 2024) and announcements of the Energy Regulatory Office (URE, 2025a, 2025b, 2025c, 2025d, 2024a, 2024b, 2024c, 2024d, 2023) document the growing number of hours with negative prices and the increasing scope of challenges in accounting for RES production, including the requirement to adjust renewable energy certificates when prices remain below zero for an extended period. The obligation to correct applications for renewable energy certificates derives from the provisions of the Renewable Energy Sources Act (RES Act, 2023). According to this Act, a certificate of origin is not granted for electricity generated in a RES installation during delivery hours in which the volume-weighted average Day-Ahead Market price (TGEBase index) was below zero Polish zloty per MWh for at least six consecutive hours.

Legal and tax analyses conducted by MDDP experts (MDDP, 2023, 2024) clearly indicate that, under the Polish tax system, transactions concluded at negative prices cannot be treated as a classical supply of goods within the meaning of the VAT Act. Their findings also point to divergent approaches across EU member states (Eurostat, 2025), even though the framework is defined by Council Directive 2006/112/EC (Council Directive, 2006).

Despite the growing academic and professional interest in negative electricity prices, both in Poland and abroad, there remains a lack of comprehensive studies combining a detailed legal-dogmatic analysis of their consequences within the Polish legal order with an assessment of actual market data. Most existing publications focus either on the economic or technical

dimensions of the phenomenon, or on the analysis of selected tax interpretations. To date, however, no systematic and interdisciplinary study has been carried out on the VAT implications of negative electricity prices, based on empirical evidence from the Polish market. This research gap justifies the present study, which aims to provide an in-depth analysis of the tax consequences of negative electricity prices in Poland, taking into account current jurisprudence, rulings of tax authorities, and market data.

3. Methods

The study is based on three fundamental components: an analysis of empirical data from the Polish Power Exchange, a legal-dogmatic analysis, and case studies from the Polish electricity market.

For the empirical analysis, hourly settlement prices of electricity from the Day-Ahead Market (Fixing II) for the period from January 2023 to June 2025 were used, as published by TGE. The hourly settlement price under Fixing II represents a reference value determined for each delivery hour on the Day-Ahead Market, reflecting the market equilibrium between submitted demand and supply while accounting for the possibility of cross-border electricity exchange. It is a volume-weighted average transaction price for each delivery hour, expressed in PLN/MWh, excluding taxes and transmission costs.

The empirical data from the Day-Ahead Market covering this period were subjected to descriptive statistical analysis. The study identified the frequency, duration, and depth of negative price episodes, as well as their distribution over time (hours, days, months). This quantitative assessment was combined with a qualitative analysis of the associated legal and fiscal implications, in order to link observed market phenomena with interpretative and regulatory issues in VAT law.

The legal-dogmatic analysis encompasses the provisions of the Polish VAT Act in the context of the implementation of Council Directive 2006/112/EC, as well as individual tax rulings issued by the Director of the National Tax Information Office, and the case law of the Regional Administrative Courts, the Supreme Administrative Court, and the Court of Justice of the European Union. In relation to the CJEU case law, only those parts of the reasoning invoked by the Polish tax authorities were taken into account.

The case study component covers selected situations from the Polish electricity market, in particular the analysis of more than thirty individual tax rulings issued by the National Tax Information Office between 2018 and 2025 concerning the settlement of transactions concluded at negative prices and their classification for VAT purposes. The selection criteria included the subject matter of the ruling (negative electricity prices), the issuing authority (National Tax Information Office), and the relevance to VAT classification issues. This material makes it

possible to identify interpretative inconsistencies and to examine the evolution of administrative practice over time.

The chosen methodological framework is particularly suited to the subject of this study. The combination of descriptive statistical analysis with a legal-dogmatic approach allows not only for documenting the dynamics of negative electricity prices, but also for examining their fiscal and regulatory consequences in VAT law. This design ensures that the economic phenomenon is analysed in direct connection with its legal and administrative treatment, which is essential for understanding the complexity of the problem.

The research focuses exclusively on the realities of the Polish electricity market, without an in-depth comparative analysis of foreign markets. This narrowing of scope makes it possible to account for domestic legal, fiscal, and market conditions in detail, while ensuring a high degree of precision in examining the consequences of negative electricity prices within the Polish power system.

4. Results

4.1. Characteristics of the Phenomenon of Negative Electricity Prices in Poland

In recent years, Poland has experienced a dynamic expansion of renewable energy sources, particularly wind and photovoltaic (PV) power. This growth, supported by subsidies and the climate policy objectives of the European Union, has reshaped the structure of the electricity market. Increasingly, phenomena already familiar to more developed energy markets – such as negative electricity prices – are being observed in Poland.

Empirical data for January 2023–June 2025, covering hourly electricity prices within Fixing II of the Day-Ahead Market, confirm the intensification of this phenomenon in recent years (Instrat, 2025). The number of hours with negative prices, their share in total trading hours, as well as minimum and average values are shown in Table 1.

Table 1.
Statistics on Hours with Negative Electricity Prices on the Day-Ahead Market, 2023-2025

Year	Number of hours in period	Hours with negative prices	Share	Lowest price [PLN/MWh]	Average negative price [PLN/MWh]
2023	8760	43	0.49%	-59.82	-22.07
2024	8783	204	2.32%	-266.06	-42.98
2025	4343	259	5.96%	-569.07	-73.45
Total	21,886	506	2.31%	-569.07	-56.80

Note. Data for 2025 cover the first half of the year.

Source: Author's own elaboration based on Instrat (2025).

In 2023, Poland recorded 43 hours of negative electricity prices, accounting for just 0.5% of all hours that year. The lowest hourly price reached -59.82 PLN/MWh, with an average negative price of -22.07 PLN/MWh. In 2024, the number of hours with negative prices rose to 204 (2.3% of all hours), with a minimum of -266.06 PLN/MWh and an average of -42.98 PLN/MWh.

The first half of 2025 saw a further intensification: 259 hours of negative prices were recorded, representing nearly 6.0% of all hours in the period. The lowest hourly price reached -569.07 PLN/MWh, while the average was -73.45 PLN/MWh.

Daily data confirm the increasing frequency of negative prices at the day level as well. Statistics presented in Table 2 show a steady rise in the number of days with negative hourly prices during the analysed period.

As shown in Table 2, only five days in 2023 (1.4% of all days) recorded hours with negative prices. In 2024, this number rose to 49 (13.4%), and in the first half of 2025 it reached 55 days, or 30.4% of the period.

Table 2.
Statistics on Days with Negative Electricity Prices on the Day-Ahead Market, 2023-2025

Year	Number of days in period	Days with negative prices	Share	Lowest daily price [PLN/MWh]	Average negative daily price [PLN/MWh]
2023	365	5	1.37%	-59.82	-20.30
2024	366	49	13.39%	-266.06	-32.66
2025	181	55	30.39%	-569.07	-60.35
Total	912	109	11.96%	-569.07	-44.08

Note. Data for 2025 cover the first half of the year.

Source: Author's own elaboration based on Instrat (2025).

In recent years, there has been not only an increase in the number of hours with negative prices, but also a rising number of days in which such episodes occur, along with greater depth of price reductions.

4.2. Legal and Tax Aspects of Negative Prices in the VAT Context

The sharp increase in the frequency of negative electricity prices on the Polish market in recent years has created new challenges for the correct VAT treatment of such transactions. Situations in which the supplier pays the purchaser to take delivery of electricity are atypical and are not explicitly addressed either in domestic legislation or in Council Directive 2006/112/EC (Council Directive, 2006), which forms the basis for VAT harmonisation in the European Union.

A key question is whether transactions concluded at negative prices can be regarded as a supply of goods within the meaning of Article 7 of the VAT Act (VAT Act, 2004) and, if so, how to determine the taxable amount and the parties' tax obligations. In practice, this gives rise to numerous interpretative uncertainties among market participants and tax authorities alike, as reflected in individual tax rulings and administrative court judgments.

The cornerstone of VAT harmonisation in the EU is Council Directive 2006/112/EC on the common system of value added tax (Council Directive, 2006). Article 14(1) provides that a "supply of goods" means the transfer of the right to dispose of tangible property as owner. In the context of electricity trading, this encompasses any transaction in which electricity is actually delivered to the purchaser in exchange for consideration. Article 73 of the Directive defines the taxable amount as "everything which constitutes consideration obtained or to be obtained by the supplier from the purchaser or a third party for such supplies or services", irrespective of the form of consideration. These provisions, however, do not address, *expressis verbis*, situations in which the transaction price is negative.

The Directive has been implemented in Poland by the Act of 11 March 2004 on Value Added Tax (VAT Act, 2004). Article 7(1) reiterates that a supply of goods is the transfer of the right to dispose of goods as owner, while Article 2(6) expressly lists electricity as a good. Under Article 29a(1), the taxable amount is "everything which constitutes consideration received or to be received by the supplier from the purchaser, the service recipient or a third party…". As drafted – similarly to the EU rules – this provision does not regulate the determination of a negative taxable amount.

An analysis of individual rulings issued by the Director of the National Tax Information Office indicates that, in cases of negative prices, the prevailing view is that the purchaser – by receiving remuneration from the seller – renders a taxable service to the seller consisting in the intake or disposal of electricity. The taxable amount is then the absolute value of the negative price, and the VAT rate is determined according to the nature of that service (most commonly 23%). This is evidenced by a broad review of tax rulings – over thirty decisions issued by the Director of the National Tax Information Office between 2014 and 2024 – whose common denominator was the VAT treatment of electricity transactions at negative prices (DKIS Rulings, 2014-2024).

Illustrative examples include the ruling of 2 February 2024 (DKIS Ruling, DP, 2024). It held that where, within a given settlement period, some hours record negative prices but the overall settlement for the period is positive, the generator should issue an invoice for the net amount corresponding to that result. Conversely, where the consideration for the entire volume delivered in the settlement period is negative, it should be recognised that the Company rendered to the generator a service of electricity intake within the meaning of Article 8(1) of the VAT Act and should issue a VAT invoice to the generator. A similar position was expressed in the ruling of 9 April 2024 (DKIS Ruling, AK, 2024), which stated that where the settlement price for electricity is negative, the purchaser incurs a VAT obligation in respect of a service rendered to the seller consisting in accepting deliveries under conditions of oversupply. This is not a supply of goods within Article 7, but a separate, taxable service. In each case, the authority emphasised that negative-price scenarios do not constitute a supply of goods within Article 7 of the VAT Act but rather a service from which the original seller is the beneficiary.

Convergent views were adopted by the Warsaw Regional Administrative Court in judgments of 19 February 2014 (WSA 2602/13, 2014), 18 January 2024 (WSA 2124/23, 2024), and 21 February 2024 (WSA 2083/23, 2024). In the judgment of 19 February 2014, the court held that a transaction involving delivery of electricity together with a payment to the recipient does not constitute an onerous supply of goods but should be classified as a separate service. In the judgment of 18 January 2024, the court stressed that, where prices are negative, electricity is not a good sold for consideration but the subject of a service whose beneficiary is the original seller. In the judgment of 21 February 2024, the court found that a negative price represents remuneration to the purchaser for accepting electricity under oversupply conditions, thereby justifying taxation of that activity as a service within the meaning of Article 8 of the VAT Act.

In certain fact patterns – e.g. settlements arising from DSR programmes (demand reduction) or participation in balancing mechanisms – the authorities indicate that the payment made to the purchaser constitutes remuneration for a separate service (load reduction, provision of flexibility) to be taxed according to the rules applicable to those services. Less frequently, decisions treat the negative price solely as a pricing component within a single commercial contract – without identifying an additional service – in which case the settlement difference alone does not give rise to separate VAT obligations.

To organise the foregoing considerations, Table 3 presents a synthetic overview of the legal classification of negative-price transactions under various scenarios, together with the determination of the taxable amount, the VAT characterisation of the activity, and the applicable tax rate.

Table 3.
Legal Classification of Transactions with Negative Electricity Prices

Transaction variant	Taxable amount	Legal classification	VAT rate
Sale of electricity at a positive price	Sale price	Supply of goods (Article 7 of the VAT Act)	23% or reduced rate under applicable provisions
Sale of electricity at a negative price – settlement period result positive	Aggregate positive value for the period	Supply of goods	23% or reduced rate
Sale of electricity at a negative price – settlement period result negative	Value of the top-up	Provision of services by the purchaser (Article 8 of the VAT Act)	23%
Top-up under DSR mechanism or system services	Value of the top-up	Provision of services by the energy recipient	23% or service-specific rate
Cross-border transactions – reverse charge	Transaction value	Supply of goods or services, depending on classification	Reverse charge – VAT settled by the purchaser

Source: Author's own elaboration.

5. Discussion

The empirical results confirm a sharp intensification of negative electricity prices in Poland between 2023 and mid-2025. However, the interpretation of these findings requires a broader discussion of their economic, operational, and legal implications.

From an economic and market perspective, negative prices are primarily driven by the rapid expansion of renewable energy sources (RES), especially photovoltaic and wind power. Their increasing share in the energy mix, supported by EU climate policy and national subsidy mechanisms, has led to situations in which supply exceeds demand, particularly during weekends or holidays with favourable weather conditions. Unlike in more mature Western European markets, the Polish power system remains relatively inflexible. Coal-fired units with high technical minimum generation levels cannot easily reduce output, while the scale of energy storage and demand-side flexibility tools, such as Demand Side Response (DSR), is still limited. These structural features of the system make the Polish market especially vulnerable to episodes of oversupply, resulting in deeper and more frequent negative price events.

The effects of negative prices are unevenly distributed among stakeholders. Conventional electricity producers face significant reductions in profitability and are often forced to curtail production. Certain RES producers operating within support schemes may remain relatively insulated, as guaranteed payments compensate for market losses. Others, especially outside such schemes, are exposed to the phenomenon of price cannibalisation and increasing risks of liquidity shortages. Transmission and distribution system operators encounter new challenges related to balancing the system, improving forecasting, and investing in storage capacity and flexibility solutions. For consumers, the potential benefits are limited: while industrial consumers with access to wholesale markets may capture some cost reductions, household customers rarely experience noticeable savings due to fixed charges and taxes that dominate retail bills.

Investment dynamics are also affected. On the one hand, negative prices highlight the urgent need to accelerate investments in storage technologies, flexible generation, and demand-side management. On the other, their growing frequency and depth may destabilise support schemes, undermine investor confidence, and deter new RES projects if market rules are not appropriately adjusted.

From a legal and fiscal perspective, the situation is equally complex. The absence of explicit provisions in both the VAT Directive (2006/112/EC) and the Polish VAT Act has produced significant interpretative inconsistencies. Tax authorities have alternately classified “top-up” payments associated with negative prices either as remuneration for services or as a pricing element within a single transaction. Administrative courts have largely followed the service-based interpretation, considering that the purchaser provides a service to the seller by accepting

electricity under oversupply conditions. However, divergent positions continue to emerge, particularly in cases linked to balancing mechanisms or DSR programmes.

These ambiguities carry important consequences. Market participants are compelled to seek individual tax rulings to ensure correct VAT settlement, which generates costs, prolongs decision-making, and increases fiscal risk. Cross-border electricity trade introduces additional uncertainty, as the reverse charge mechanism applies but national practices differ in the treatment of top-ups. Furthermore, unresolved issues concern the right of RES producers to deduct input VAT in cases involving negative settlements. Without clear rules, this uncertainty may undermine the financial stability of RES projects and complicate the functioning of capacity market and system service mechanisms.

The results of this study are consistent with findings in the broader literature, while at the same time extending them. Similar to the analyses of Reichenberg, Hirth and Söder (2021), the Polish market exhibits the price cannibalisation effect, but in Poland the phenomenon is amplified by the lower flexibility of the power system and the dominance of coal-based generation. Whereas most international studies (e.g. Eurelectric, 2024; ICIS, 2024) focus on the technical and economic dimensions of negative prices, this article makes a novel contribution by highlighting their VAT implications. In this respect, it establishes what was previously absent from the literature: a systematic legal-dogmatic analysis of how negative electricity prices are treated under Polish and EU VAT law.

From a methodological perspective, the study confirms existing observations on the rising frequency and depth of negative prices (e.g. Instrat, 2025), but it also expands the scope of knowledge by showing their tax consequences. This integrated approach – linking empirical data with legal analysis – creates a stronger alignment between the literature review, methodology, and discussion, and responds directly to the reviewer's questions concerning the originality and added value of the research.

Overall, the discussion highlights that negative electricity prices in Poland are not only an increasingly frequent empirical reality but also a source of profound market, legal, and fiscal challenges. Addressing these issues requires coordinated reforms: technical measures to increase system flexibility, regulatory adjustments to stabilise support schemes and encourage investment, and legislative clarification of VAT rules to reduce legal uncertainty. Without such steps, the accelerating phenomenon of negative prices risks weakening both the energy market and the effectiveness of climate policy instruments in Poland.

6. Conclusions

The analysis of negative electricity prices in the VAT context demonstrates that the absence of specific legal provisions – both at EU and domestic level – leads to significant divergences in interpretative and judicial practice. Council Directive 2006/112/EC and the Polish VAT Act define the supply of goods and the taxable amount in general terms, without providing tailored solutions for transactions in which the price assumes a negative value. As a result, tax authorities and administrative courts rely on functional interpretation, often concluding that such cases involve the provision of services to the electricity seller, rather than the supply of goods.

The identified gaps and issues concern, above all: the lack of a uniform approach to the classification of top-up payments; the absence of comprehensive guidelines on cross-border settlements; uncertainty as to the right of electricity producers to deduct input VAT; and the ambiguous distinction between top-ups as a pricing component of electricity and remuneration for separate services under capacity market and system service mechanisms.

Against this backdrop, legislative and interpretative measures appear warranted, aimed at clarifying the VAT Act by introducing definitions or guidelines for the treatment of transactions at negative prices in the electricity market, including the rules for determining the taxable amount. It is also necessary for the Ministry of Finance or the National Tax Information Office to issue uniform tax guidance that would consistently regulate the classification of top-ups in both domestic and cross-border transactions, and to harmonise practice in cross-border settlements by aligning Polish regulations and interpretation with standards applied in other EU member states. Equally important is the development of criteria for distinguishing between a top-up as an integral pricing element and as remuneration for a separate service, for instance under DSR programmes or balancing mechanisms. Consideration should also be given to the implications for the renewable energy sector, particularly ensuring clear rules on input VAT deduction, which are of critical importance for the financial stability of RES projects.

At the same time, it should be emphasised that the implementation of such legislative or interpretative clarifications may encounter certain constraints. At the EU level, VAT rules are subject to harmonisation under Directive 2006/112/EC, which limits the possibility of adopting fully autonomous domestic solutions. Furthermore, political economy factors – such as divergent interests among market participants and the potential fiscal implications for national budgets – may affect both the scope and the pace of reform. Acknowledging these challenges is essential for assessing the feasibility and durability of the proposed recommendations.

The implementation of these measures would substantially reduce legal and tax uncertainty for market participants, enhance the predictability of settlements, and lower the risk of disputes with tax authorities. In the longer term, such measures could also contribute to improved functioning of market mechanisms in the energy sector, especially under conditions of increasing price volatility and the dynamic growth of renewable energy sources.

In view of the above recommendations, it is worth assessing the potential fiscal effects of their implementation for the state budget, both in the short and long term. Introducing precise rules for the VAT treatment of transactions at negative prices could have material implications for budget revenues. Positive outcomes would include greater legal certainty, a reduction in tax disputes, and potentially higher VAT inflows as a result of the uniform application of rules classifying top-ups as taxable services. On the other hand, clarification of the law could expose cases where top-ups are currently not treated as taxable consideration, thereby increasing the tax burden for certain market participants but also boosting current budget revenues. In the medium and long term, the fiscal impact would depend on the frequency of negative price episodes and on the market structure – particularly the share of cross-border transactions subject to the reverse charge mechanism, which may limit direct VAT inflows in Poland. At the same time, improved stability of tax settlements could indirectly support RES development and, consequently, contribute to the achievement of climate policy objectives, which is significant for the financing of public policies.

Limitations and weaknesses of the study must be acknowledged. The analysis was restricted to the Polish electricity market and relied primarily on empirical data from the Day-Ahead Market (January 2023–June 2025). The findings therefore capture a specific temporal and national context, without extending to comparative assessments of other EU jurisdictions. Moreover, the fiscal dimension of the study was based on the available body of tax rulings and court judgments, which reflect interpretative practice rather than clear statutory provisions.

Nevertheless, the study contributes new knowledge by systematically linking empirical evidence on negative electricity prices with an in-depth legal-dogmatic analysis of VAT consequences. Unlike most previous works, which emphasised economic or technical aspects, this article highlights the fiscal implications of negative prices and their potential impact on the financial stability of renewable energy projects.

The importance of the research lies in demonstrating how the accelerating phenomenon of negative electricity prices intersects with legal uncertainty in VAT law. The results are relevant not only for tax authorities and market participants but also for policymakers seeking to balance fiscal stability with climate and energy policy objectives.

A promising avenue for future research would be to other EU member states in order to evaluate whether similar interpretative divergences occur and to explore the prospects for harmonisation. Comparative studies could also assess the extent to which national practices align with or diverge from the principles established under Council Directive 2006/112/EC.

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FUTURE ELECTORAL CHALLENGES IN POLAND: AN ANALYSIS OF PROCESSES AND VOTER TURNOUT IN 2000-2024

Sławomir OSTROWSKI[1*], Maciej KWIDZIŃSKI[2]

[1] Gdańsk University of Technology, Faculty of Management and Economics; slawomir.ostrowski@pg.edu.pl, ORCID: 0000-0002-1969-0844
[2] Gdańsk University of Technology, Faculty of Management and Economics; maciejkwi2003@gmail.com, ORCID: 0009-0006-0617-7693
* Correspondence author

Purpose: This study analyzes the evolution of electoral processes and voter turnout in Poland (2000-2024), focusing on technological innovations to improve election efficiency, transparency, and inclusiveness. It assesses voter participation trends and key challenges to provide insights for future electoral improvements.
Design/methodology/approach: The study uses mixed methods, combining voter turnout analysis, surveys of electoral commission members, and a review of materials to evaluate procedural guidelines and member preparedness.
Findings: Voter turnout increased for parliamentary and presidential elections but remained low for European Parliament elections and referendums. Challenges include inefficiencies in vote counting, protocol preparation, and technological readiness. Innovations like automated counting and biometric authentication offer promising solutions.
Practical implications: These findings underscore the need for targeted reforms in electoral training, procedural efficiency, and technological integration. These recommendations can guide policymakers and electoral authorities to design robust and citizen-friendly election systems.
Originality/value: This study offers a comprehensive assessment of electoral processes in Poland over the past two decades by combining historical data analysis with practical insights from members of the electoral commission. The inclusion of a technological perspective provides a novel perspective, highlighting the potential of digital transformation to modernize electoral systems.
Keywords: elections, electoral processes, voting, voter turnout, elections in Poland.
Category of the paper: Research paper.

1. Introduction

A person's life involves the constant need to make choices. An example of decision making in social and political life is participation in national elections. During elections, one fulfils one's civic duty by electing from among the candidates one's representative for a given position, such as the president or a member of parliament. Election time is unique because of its importance for the future functioning of the country and mass participation of citizens, which poses many organizational challenges. The work of electoral commissions is integral to the organization of elections. It is through relevant bodies and offices that the government can organize and conduct elections.

The District Electoral Commissions (DEC), which is an organizational unit of the National Election Commission (NEC), is responsible for voting and determining its results. This includes tasks such as counting and stamping ballots, verifying the identity of the voter, keeping the polling station in order, manually counting the completed ballots, completing voting records, and delivering election materials to the relevant office. Some of the processes listed above are complex and time consuming. An example is the counting of ballots, which requires manual counting of several thousand paper ballots and can take up to several hours. In the 2023 parliamentary and senate elections, some DECs were forced to work until the early morning hours by an unexpectedly high voter turnout. There was a shortage of ballot papers at some polling stations, and long and complex voter ID verification resulted in large queues outside the polling stations.

The aim of this work is to diagnose electoral processes that are problematic and in need of improvement, which will be served by feedback obtained through a survey of people with experience working in an electoral commission. The next step was to analyze and identify their weaknesses. Finally, we discuss suggestions for technological solutions that can improve electoral processes in the future.

2. Literature Review

In academic literature on electoral processes, the theoretical context plays a key role in understanding the basic concepts and mechanisms involved in the functioning of contemporary democratic systems. Understanding democracy as a system of governance, the role of national elections as a tool for its implementation, and the organizational structures responsible for voting provide the foundation for analyses related to the impact of technological change on electoral processes. This chapter provides a starting point for a more detailed analysis of electoral practices in Poland and the world.

2.1. Democracy

The term 'democracy' can be used to describe a political system in which the affairs of the government are decided by a majority vote of all citizens. Democracy dates back to the sixth century BC and originated in ancient Athens. The particle is the precursor to democracy. People have exercised their sovereign powers. The essence of Athenian democracy was the equality of citizens before the law, access to office, common unanimity, and rule of law (Cabaj et al., 2013). A modern democratic government is one where elected representatives, chosen through free elections, exercise power. It is defined by political and civil rights such as freedom of speech, the right to vote, and participation in fair and free elections. Public officials are selected through elections and held accountable to the public (Bankowicz, 2006). The Constitution, as the supreme legal act, plays a central role in a democratic government. It outlines the structure of government, the rights and duties of citizens, and procedural regulations for authorities. In a democratic state, power is divided into three branches: legislative, executive, and judicial (Bankowicz, 2006). In Poland, legislative power is exercised by the Sejm and the Senate, which enact laws and establish legal frameworks. Executive power is held by the President and the Council of Ministers, who implement the laws passed by parliament. Judicial power is vested in courts and tribunals, which uphold, rather than shape, the law in the country (Bankowicz, 2006).

2.2. The concept of national elections

According to the Polish Language Dictionary, an election appoints suitable candidates for specific functions through voting. In light of democracy, elections are a democratic tool that consists of citizens' selection through voting for representatives who exercise political power (Bankowicz, 2006).

Elections to Sejm in Poland were conducted in five rounds, as defined by the following principles (Helsinki Foundation for Human Rights, 2020):

- the principle of directness is to vote for a candidate for a specific position,
- the principle of equality, means that each voter has an equally valid vote,
- the principle of universality, a country in which every citizen with an active right to vote has the right to participate,
- proportionality principle: Each group receives a number of seats in proportion to the number of votes it receives in the election,
- the secrecy of the ballot is preserved by not signing ballot papers - no one will know for whom a citizen has voted.

2.3. Electoral bodies responsible for conducting elections

According to Article 152 of the Election Code, the permanent bodies responsible for conducting elections are the National Election Commission (NEC) and election commissioners.

The bodies appointed in connection with the organization of the elections are, in turn, district, district, territorial, and regional election commissions. The main electoral bodies functioning in Poland, according to the Election Code, are presented below:

The National Election Commission (NEC) (in polish PKW) is the highest electoral authority in Poland, which is associated with the organization of elections and referenda. The tasks include, inter alia, supervising the observance of election laws, appointing and dissolving election commissions (district and regional), announcing voting and election results, and commissioning the National Election Office to handle elections.

The National Election Office (NEO) (in polish KBW) provides services to the NEC and other bodies related to holding elections. The tasks of the NEO include, inter alia, servicing the NEC, organizing elections and referendums, providing organizational and administrative conditions, and preparing training for members of the DEC.

The district electoral commission is a commission of four members with a university degree in law. The task of the district electoral commission is, inter alia, to comply with electoral law, ensure the delivery of ballot papers to district electoral commissions, and ensure the performance of electoral tasks in cooperation with officials and relevant local government units.

The territorial election commission was appointed by the election commissioner no later than 40 days prior to the election. The territorial election commission has three components: the provincial election commission, district election commission, and municipal election commission. The duties of the territorial election commission include registering candidates for councillors, ordering the printing of election notices, dealing with complaints lodged against the activities of the district election commission, and sending the vote and election results to the election commissioner.

The District Election Commission (DEC) describes as one of the organs of the NEC, which is responsible for the practical conduct of voting and determination of voting results in elections and referendums in a given polling district in Poland. DEC is the lowest among election commmissions. The DEC is headed by a chairperson and deputy chairperson elected at the first meeting. They were responsible for managing the commission's work before and on the polling days. The tasks of the DEC include preparing the polling station for the election, serving the voter, guarding the ballot box, counting the ballots, completing voting records, and transferring election materials to the relevant office (Electoral Code).

2.4. Electoral processes

The electoral process occurs earlier than the voting day, during which the voter puts the cast vote in the ballot box. It consists of a number of other activities, such as campaigning, registering electoral committees, and counting votes. These activities are carried out only by authorized entities or electoral bodies, which operate on the basis of procedures and regulations found in the Constitution or the Electoral Code (Maksymiuk, Pastuszko, 2023). In Poland, Sejm elections are ordered by the President and announced via the Public Information Bulletin.

Election campaigning begins with the announcement and ends 24 hours before polling day. Polling districts are established a month before the election, while election committees are appointed 21 days prior, with members selected by the return officer based on population proportions. Candidate nominations close 40 days before the election, with the DEC verifying eligibility. Ballots are printed and distributed after candidate registration is complete. Preparations for election day occur the day before, including setting up polling stations and distributing materials. On election day, voting takes place from 7-21, with voters verifying their identity and casting ballots. After polls close, ballots are counted, results are recorded, and voting records are finalized. Results are validated and announced publicly, with a report sent to the President, the Speaker of the Sejm, and the Supreme Court two weeks after the NEC announces the results (Electoral Code).

3. Research methodology

This study used a mixed-methods approach that combined both quantitative and qualitative data analyses. An analysis of historical data on voter turnout and a survey of DEC members were carried out to gain insight into the practical aspects of the operation of electoral systems. In addition, a thorough analysis of the training materials received from the NEC was prepared for the training of elected mission members.

3.1. Data sources

3.1.1. Quantitative data

Data on voter turnout in Poland between 2000 and 2024 are obtained from the NEC. The data included turnouts from presidential elections, parliamentary elections, and national referendums. The dataset was analyzed to identify trends, anomalies, and the potential impact of electoral technologies on voter behavior.

3.1.2. Qualitative data

On 09.06.2024 (after the European Parliament elections), questionnaires were presented to the members of the DECs. A questionnaire survey was conducted on a group of 43 people who served as members of the DECs in these elections in various localities in the Pomeranian Voivodeship. The survey focused on examining the experiences of DEC members during elections organized by the NEC. The questionnaire consisted of thirteen questions. Two questions qualified the respondents for the survey, seven factual questions on the research problem, and four metric questions characterizing the respondents. The purpose of the survey was to understand the problems and needs of the DEC members. The questionnaire covered topics such as a member's previous experience of participating in election commissions, his or her assessment of the various stages involved in conducting elections, and suggestions

for improving the work of DEC members. Open-ended questions allowed for the identification of subjective opinions and observation of the challenges and benefits of process-driven changes in the electoral process. Additionally, training materials developed by the NEC for the training of election commission members were analyzed. These documents include guidelines on organizational procedures, the operation of technological systems, and the principles of election security. Particular emphasis was placed on the content of the sections on handling technology, such as ICT systems, that support electoral processes. Analysis of the materials made it possible to assess the preparedness of electoral commission members to perform their duties and to identify potential challenges arising from the implementation of new technologies.

3.2. Data analysis process

3.2.1. Quantitative data analysis

Attendance data were subjected to statistical trend analysis and inter-cyclical comparisons using Excel. The averages, medians, and standard deviations were calculated. Data visualization methods, such as line graphs and bar charts, were used to clearly present the results.

3.2.2. Qualitative data analysis

Survey results were coded and classified into key thematic categories. Content analysis made it possible to identify recurring patterns and differing opinions among the respondents. A detailed analysis of the training materials developed by the NEC that were used during the training of election commission members was carried out. These materials were assessed in terms of the details of the information they contained and their relevance to the needs of commission members. Particular attention was paid to electoral processes. The extent to which these materials support the effective implementation of new technologies and ensure adherence to the guidelines of the NEC was also analyzed to assess the level of preparation of commission members for their electoral duties.

3.3. Research limitations

The number of respondents to the survey, while providing valuable information, was not fully representative of all the DEC members. Survey results may also be affected by the subjectivity of the responses, which must be considered when interpreting them.

3.4. Stages of the study

This study was conducted in several stages, as follows. Turnout data were collected from the NEC resources. Next, a survey of the election commission members was conducted. The next step was the analysis of quantitative and qualitative data, which made it possible to identify the trends and significant correlations. This was followed by a thorough analysis of the NEC training materials. Finally, the results were interpreted. This methodology allows for

a multifaceted analysis of voter turnout and an assessment of electoral processes, taking into account both quantitative and qualitative perspectives.

4. Results

4.1. Analysis of voter turnout data in Poland from 2000 to 2024

Over a 24-year period (2000-2024), 37 votes (elections and referendums) were held in Poland. Table 1 summarizes the turnouts for each election. In some presidential and local government elections, there was a repeat vote in the second round; the turnout during the subsequent vote is shown in the opposite column.

Table 1.
Turnout of elections and referendums held between 2000 and 2024

Year	Elections	Voter turnout (1st round of voting) [%]	Voter turnout (2nd round of voting) [%]
2000	Presidential election	61,12%	
2001	Parliamentary election	46,29%	
2002	Municipal election	44,24%	35,02%
2003	National Referendum	58,85%	
2004	European Parliament elections	20,87%	
2005	Parliamentary election	40,57%	
2005	Presidential election	49,74%	50,99%
2006	Municipal election	45,99%	39,56%
2007	Parliamentary election	53,88%	
2009	European Parliament elections	24,53%	
2010	Presidential election	54,94%	55,31%
2010	Municipal election	47,32%	35,31%
2011	Parliamentary election	48,92%	
2014	European Parliament elections	23,83%	
2014	Municipal election	47,34%	39,97%
2015	Presidential election	48,96%	55,34%
2015	National Referendum	7,80%	
2015	Parliamentary election	50,92%	
2018	Municipal election	54,90%	48,83%
2019	European Parliament elections	45,68%	
2019	Parliamentary election	61,74%	
2020	Presidential election	64,51%	68,18%
2023	Parliamentary election	74,38%	
2023	National Referendum	40,91%	
2024	Municipal election	51,99%	44,06%
2024	European Parliament elections	40,65%	

Source: own compilation based on: https://www.pkw.gov.pl/, 16.11.2024.

When analyzing turnout in the second round of elections, a certain pattern can be observed. During presidential elections, the turnout in the second round increased, while it was lower during municipal elections.

Figure 1 presents the voter turnout from 2000 to 2024, using a bar chart. Each type of election is marked with a different color.

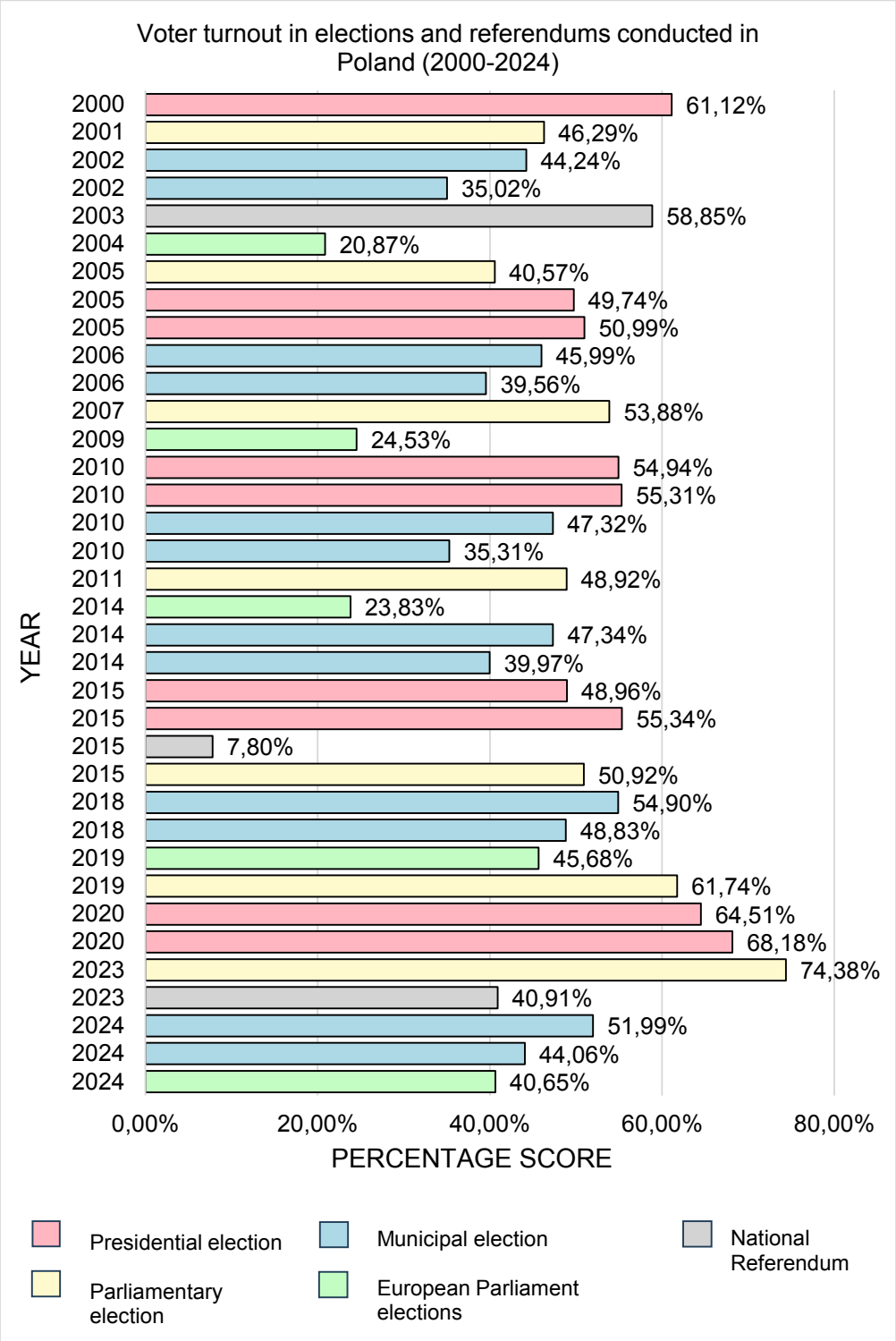


Figure 1. Turnout of elections and referendums held in the Poland between 2000 and 2024.

Source: own compilation based on: https://www.pkw.gov.pl/, 16.11.2024.

The average turnout in organized elections and referendums during the 2000-2024 election period is shown in Figure 2.

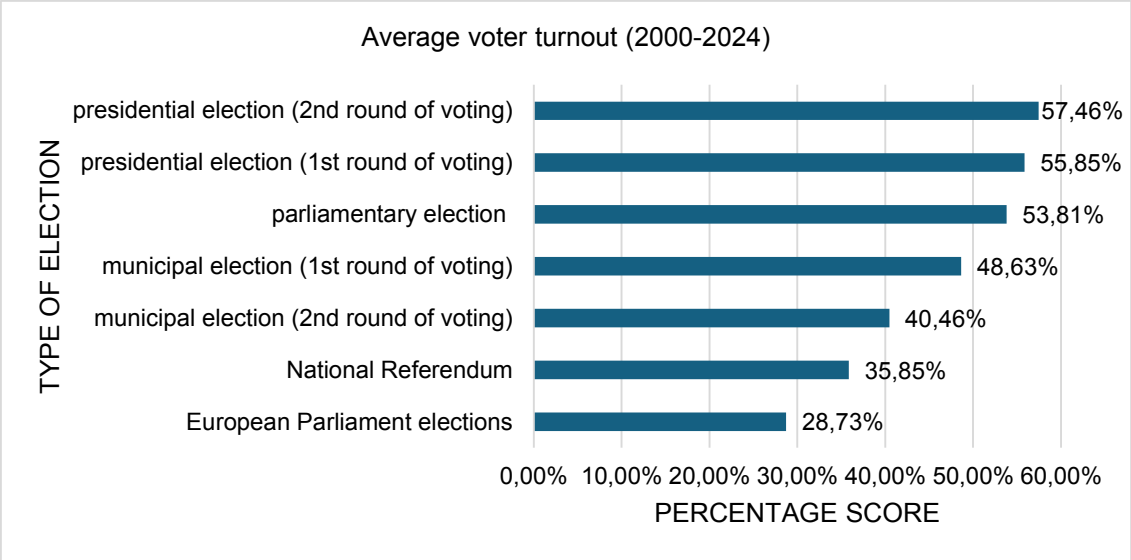


Figure 2. Average election turnout from 2000 to 2024.

Source: own elaboration.

The highest average turnout can be recorded in the second round of the election for the President of Poland, at just under 58%. This was followed by the first round of elections, with a result of almost 56%. The lowest average turnout can be seen in the European Parliament elections, as the result is below the 30% threshold.

4.1.1. Conclusions of the analysis of attendance from 2000 to 2024

In recent years, there has been a noticeable increase in interest in high-profile political elections, particularly parliamentary and presidential elections, indicating citizens' growing awareness of issues that are crucial to the functioning of the country. A particular example is the turnout recorded in 2023, which may be the result of significant socio-political events and effective mobilization efforts by political parties. The analysis also shows that the structure of voting rounds influences turnout, with the second round of presidential elections attracting more voters because of the importance of the final outcome between the main candidates. In municipal elections, on the other hand, the decrease in turnout in the second round may be due to the local nature of the voting, which limits voter mobilisation.

Challenges also arise in the context of European parliamentary elections and referendums that record the lowest turnouts. This is due to citizens' limited interest in EU issues and the specific referendum questions. This situation calls for greater promotion of the importance of these votes and raising public awareness of their impact on citizens' lives. In addition, the analysis highlights that public involvement in voting varies and depends on the nature of the elections. Votes with clear political consequences, such as presidential or parliamentary elections, involve more citizens than votes of a local or abstract nature, such as referendums with single-member constituencies.

In conclusion, elections and referendums with low turnout require the implementation of strategies to increase citizens' interests. Such measures may include voter education, more effective communication regarding the importance of voting, and the introduction of technological innovations to make voting more accessible. These findings highlight the need for further analysis and development of effective public mobilization strategies to increase citizen engagement in electoral processes.

4.2. Survey

The study involved adult women and men residing in Pomorskie Voivodeship who served as members of the DECs in elections organized by the NEC. A total of 43 individuals were surveyed.

Of the 43 DEC members participating in the survey, 29 were women and the remaining 14 were men. The age of the respondents was quite average, but the largest group was between 18 and 29 years old, being mostly students. More than 70% of the people participating in the survey lived in towns with between a dozen and 250,000 inhabitants. The remainder lived in rural areas or larger metropolitan areas. Approximately two-thirds of the respondents had a university degree and one-third had secondary or primary education.

In response to the question, "Which stage during the work at the DEC caused the most problems?" respondents rated the difficulty of three stages in organizing elections in Poland on an ordinal scale: preparing the polling station, conducting the vote, and determining the results of the vote.

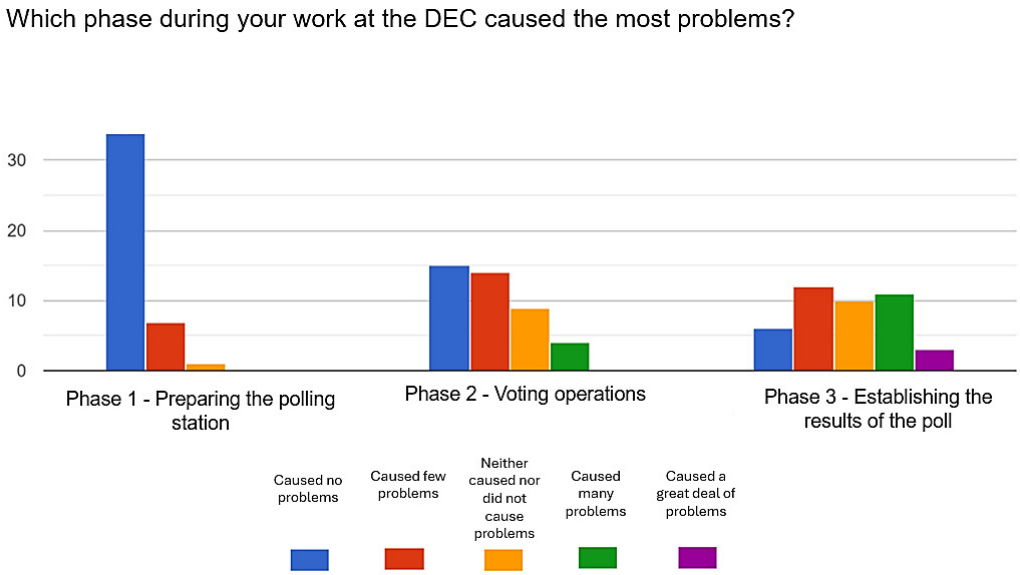


Figure 3. DEC experience survey.

Source: own elaboration.

As shown in Figure 3, a semi-open-ended question asked respondents to identify which phase during their work at the DEC caused the most problems. Over 80% indicated that the preparation of voting protocols was the most challenging process. The second most problematic

task, identified by 60% of respondents, was determining the results of the vote, specifically the process of vote counting. Other activities, such as verifying voter identities, stamping ballots, or maintaining order at the polling station, were not widely perceived as problematic. To improve DEC operations, the most popular suggestion among respondents was election digitization, supported by approximately 60%. This included automating election processes, introducing an electronic vote-counting system, and using QR technology for candidate selection. Other suggestions focused on simplifying instructions and guidelines, providing better-organized training, and offering pre-election training for DEC candidates.

Summarizing the results of the survey, members of DECs experience problems when conducting elections organized by the NEC. Approximately 90% of the respondents participated in the election as ordinary members of the DEC. The efficiency of the conduct of the last election was assessed as fairly balanced; however, almost half of the respondents assessed their last election as not very efficient in terms of organization. This was mainly reflected in the third stage of conducting elections, that is, activities related to the determination of voting results. This stage was identified as the most problematic. The processes in the previously mentioned stage that caused the most difficulties during the elections were the counting of votes and preparation of voting records. According to the respondents, these processes are too complex, resulting in lapses and mistakes made by DEC members when determining voting results. Almost 3/4 of the respondents believed that the aforementioned steps should be improved or modified. The most frequently suggested solution is the implementation and use of modern technologies for the functioning of DEC. Automation of processes, introduction of an electronic vote-counting system, and use of QR codes as a form of voting are measures that can improve the operation of the DEC and reduce the experience of problems when working in election commissions.

4.3. Analysis of electoral processes in Poland

Electoral processes play a key role in the functioning of democratic political systems by ensuring the legitimacy of power and the possibility of expressing citizens. This chapter analyze the electoral processes in Poland in detail, taking into account the process of preparing for and holding elections. Such an analysis will allow us to understand how electoral processes in Poland were shaped, and what challenges they faced in the future.

4.3.1. Process of preparing for and conducting elections

Analyzing the training materials for DEC members developed by the NEO, Figure 4 presents a process diagram containing the activities carried out during the process of preparing for and conducting elections.

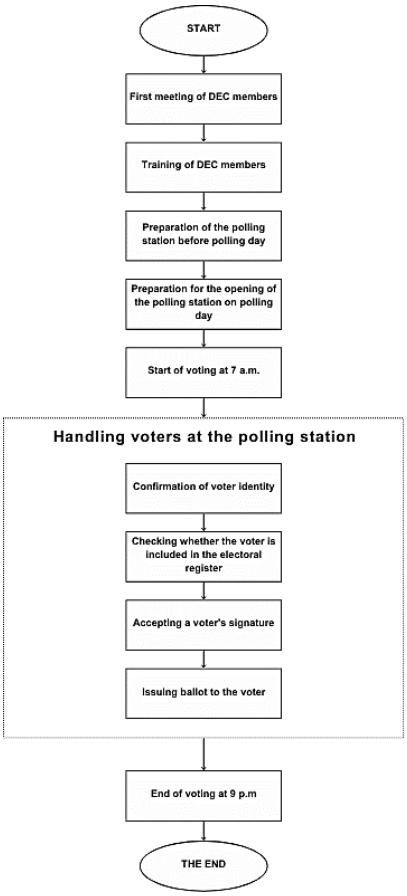


Figure 4. The process of preparing and conducting elections by DEC.

Source: own elaboration.

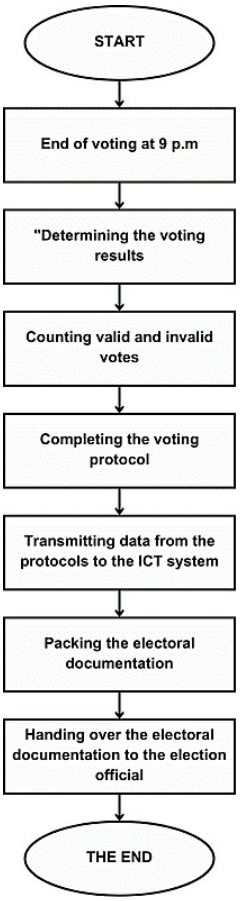


Figure 5. Process of determining the results of a ballot by DEC.

Source: own elaboration.

On polling day, before opening, the commission verifies documents, seals, recounts and stamps ballots, prepares registers and ballot papers, and ensures the station is ready. The ballot box is sealed, and all tasks must be completed by 6 a.m. Voting begins at 7 a.m., with at least half the commission present, and involves verifying voters' identity, confirming their inclusion in the register, obtaining their signature, and issuing ballot papers. Turnout data is reported at 12-17. Voting ends at 9:00 p.m. (National Election Office, 2024).

4.3.2. Process for establishing the results of votes and drawing up voting records

Analyzing the training materials for members of the DECs developed by the NEO, Fig. 9 presents a process diagram containing the activities carried out during the process of determining the voting results and drawing up voting records. Voting concluded at 9:00 p.m., marking the closure of the polling station. The ballot box was sealed, its inlet secured, and then opened to determine the results in the presence of at least two-thirds of the committee. The process included separating valid and invalid votes, counting valid votes for each candidate, and identifying reasons for invalid votes.

The committee then completed the voting protocol by counting the papers and recording the results. These results were forwarded to the IT operator for verification. After the minutes were checked, they were printed, stamped, and signed by all committee members. The finalized

protocols were uploaded to the Support for Electoral Bodies IT system, and two copies were made. One copy was posted at the polling station for public access.

Following the protocol procedures, the committee packed the election documentation. Protocols were placed in envelopes, and other documents and materials were organized into election packages. These were handed over to electoral officers. Voting records were first sent to the district electoral commission for approval. Once approved, the electoral packages were deposited with the electoral officer, who confirmed proper packing and receipt (National Election Office, 2024).

4.4. Analysis of voting patterns - Poland, Europe and the USA

Contemporary electoral processes, although rooted in democratic traditions, are subject to dynamic changes due to technological advances and cultural, legal, and organizational differences. The voting methods adopted in different regions of the world reflect the specificity of local political systems and the level of adaptation to modern challenges such as digitization, growing citizens' mobility, and the need to ensure a high level of electoral data security. This subsection presents an analysis of voting methods in Poland, Europe, and the United States. Traditional and modern voting methods, such as voting at polling stations, postal voting, electronic voting, and online voting, have been presented. This analysis will show both common trends and specific solutions that distinguish the studied regions, and identify potential inspirations for the development of electoral processes in Poland.

4.4.1. Poland

The Election Code distinguishes three ways in which one can cast a vote during elections and referendums organized by the NEC (Electoral Code): traditional voting at the premises, postal voting, and voting by proxy.

Traditional polling is the most commonly used voting method. It occurred at the polling station on the polling day between 7 a.m. and 9 p.m. It involves filling in the ballot paper given to you by a member of the polling station and dropping it into a ballot box.

Postal voting is a method of voting for voters with severe or moderate disabilities, those in quarantine, or those aged 60 years or older. Once the voter has been notified and accepted by the office of their intention to vote by post, an election packet is delivered to the voter, which contains, among other things, a return envelope, instructions with ballot papers, and a declaration of personal and secret ballots on the ballot paper. Once the voter has cast their vote and the return envelope has been properly prepared, the voter sends it back to the electoral commission, where the ballot envelope is removed from the return envelope and dropped into the ballot box.

Voting by proxy is a method of voting for voters with severe or moderate disabilities or for those aged 60 or over. After submitting an application containing the details of the person who will receive the proxy vote, the right to cast the vote is "transferred" to the designated person. On the polling day, upon arriving at the relevant electoral commission and presenting

an identity document and voting proxy certificate, the person receives ballot paper from the commission.

4.4.2. Europe

Krasnowolski (2015) distinguished additional voting methods in elections in European countries (as of 02.11.2024). Figure 6 presents the voting methods used in European countries.

	Voting methods							
	Proxy voting		Postal Voting	Electronic voting		Outside the polling station (mobile ballot box)		Others
	Based on the power of attorney	With the assistance of a third party at the polling station		In the polling station	By Internet	Mobile ballot box	Mobile polling station	
1	Albania	Croatia	Austria	Belgium	Estonia	Bosnia and Herzegovina	Austria	Austria
2	Belgium	Montenegro	Belgium	France	Switzerland	Croatia	Netherlands	Bosnia and Herzegovina
3	France	Estonia	Bosnia and Herzegovina	Moldova		Montenegro	Germany	Denmark
4	Netherlands	Spain	Estonia	Switzerland		Estonia		Lithuania
5	Poland	Lithuania	Finland			Finland		Norway
6	Sweden	Germany	France			Lithuania		Portugal
7	United Kingdom	Switzerland	Spain			Moldova		Slovenia
8			Netherlands			Norway		Sweden
9			Iceland			Russia		
10			Lithuania			Slovakia		
11			Luxembourg			Slovenia		
12			Germany			Ukraine		
13			Poland			Hungary		
14			Slovakia			Italy		
15			Slovenia					
16			Switzerland					
17			Sweden					
18			Hungary					
19			United Kingdom					
20			Italy					

Figure 6. Voting methods in European countries.

Source: Krasnowolski (2015).

The voting methods used in European countries include proxy voting, electronic voting at polling stations, electronic voting via the Internet, voting outside polling stations (mobile ballot boxes), and other voting methods.

Proxy voting with the assistance of a third party at the polling station occurs in the seven countries listed in the table, in the event that the voter is unable to cast the vote themselves there is the option to vote with the assistance of another person who is also at the polling station. To vote, this preference must be notified before the electoral commission.

Electronic voting at the polling station occurred in the four countries indicated in the table, including Belgium, where electronic voting is possible. In 2012, Venezuelan Smartmatic proposed a new electronic voting solution (Kużelewska, 2018). The voter could cast his or her vote using a touchscreen, which later allowed verification of the vote cast by printing a voting report. The printed report containing the QR code had to be scanned by the corresponding vote-counting machine and later dropped into the ballot box.

Electronic voting via the Internet is only present in two European countries: in Estonia and in Switzerland, it is possible to vote via the Internet. In Estonia, voters vote on the NEC website, and after identification, a list of candidates is displayed. A digital signature is required to confirm a vote (Czakowski, 2011).

Voting outside the polling station (mobile ballot box) occurs when a voter's health does not allow them to turn up at the polling station and cast their vote in a traditional way. The 14 countries listed in table. This involves sending two committee members to the voter's place of residence and conducting a vote outside the premises of the polling station. After verification of identity, the voter casts a vote and drops it into a ballot box, which is sealed immediately afterwards.

Some European countries have allowed early voting. Each has its own procedure and option for casting a vote. In Austria and Slovenia, it is possible to vote at an existing commission in Lithuania and Sweden at the seat of the local authority, and in Denmark, this is done through correspondence (Krasnowolski, 2015).

4.4.3. United States

The voting methods in the United States (US) are similar to those in European countries: in-person voting (in-person voting), early voting (early voting), and voting by mail (voting by mail). Figure 11 provides a summary of voting methods for US elections over the 2018-2022 period.

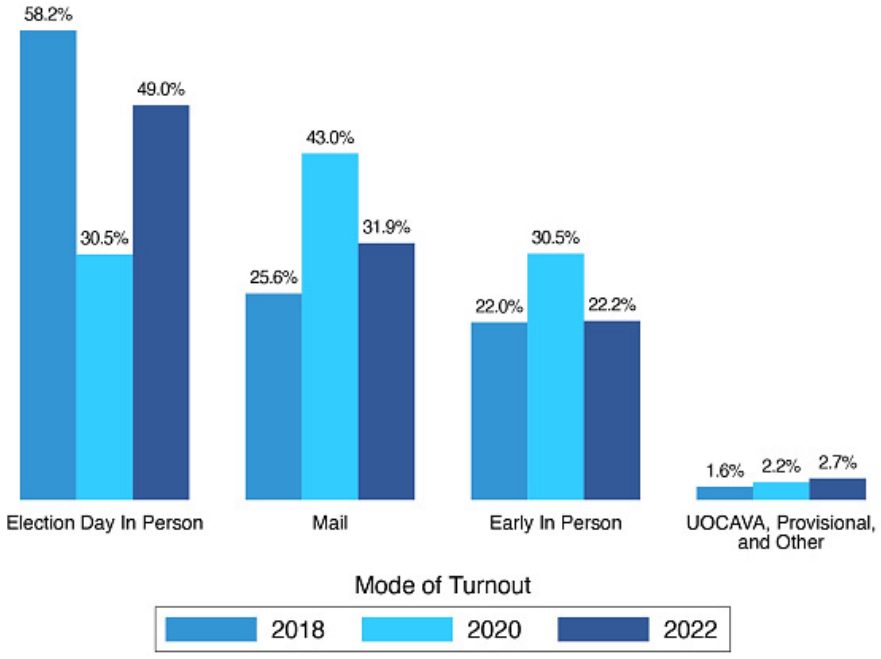


Figure 7. Preferred method of casting a ballot in the US between 2018 and 2022.

In-person voting (In-person voting) is the traditional method of voting at a polling station on an election day.

Early voting (Early voting) is an opportunity to cast a ballot before the official election day. There are two ways to cast an early vote in the US. A voter can go to a polling place or election office, obtain a ballot, cast a vote, and place the completed ballot in a ballot box or dedicated machine. In certain states, the voter can go to the polling office and take the ballot home (in some states, only the completed ballot can be taken home). Once the ballot is cast, it is sealed in an envelope and sent by a post.

Mail voting is also known as postal voting. The voter receives a postal ballot before the election, and casts a vote for a candidate at home. The final step is to send the completed ballot by mail, carrying it to the appropriate election office or, in some states, using a secure dedicated ballot box (The U.S. Election Assistance Commission, 2023).

Over the past five decades, new voting methods at polling stations have been increasingly modified and introduced in the US. With each successive election, one can see the increasing dominance of the two types of technology: scanning and Direct-Recording Electronic (DRE) (Desoi, 2018)

Figure 8 presents a list of the technology used in the United States.

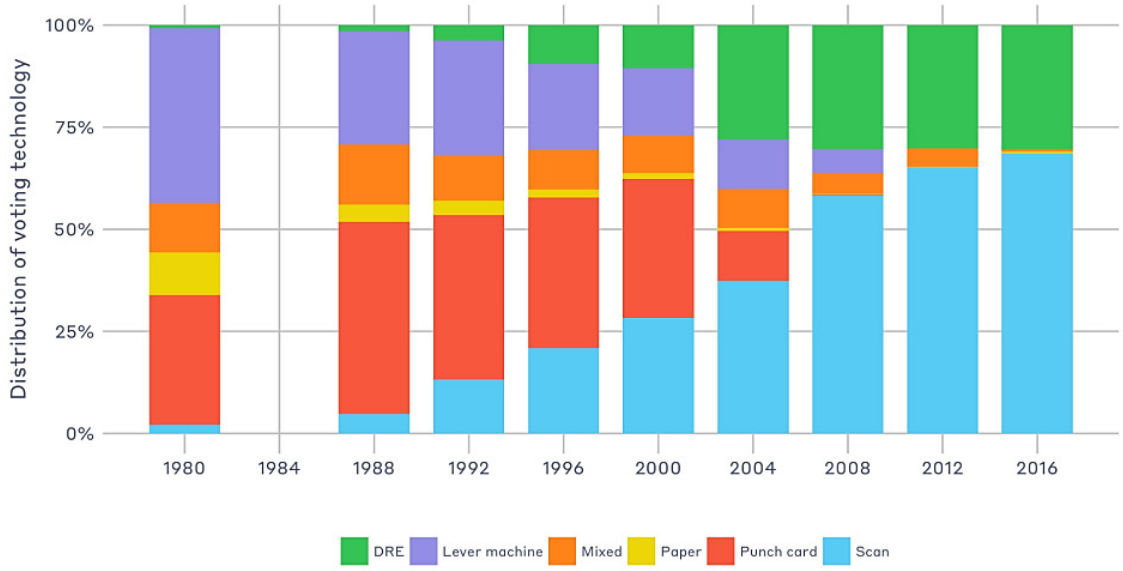


Figure 8. List of technology used in the United States between 1980 and 2016.

Source: https://electionlab.mit.edu/articles/medsl-explains-voting-technology

Currently, only a few counties use paper ballots, which are counted manually. Over the last 50 years, it is possible to see how the US has rejected the manual method of counting paper ballots in favor of technological solutions, such as Optical Scanners or DRE, which will be discussed later in this paper.

Figure 9 shows the most commonly used technologies in the US between 2020-2022.

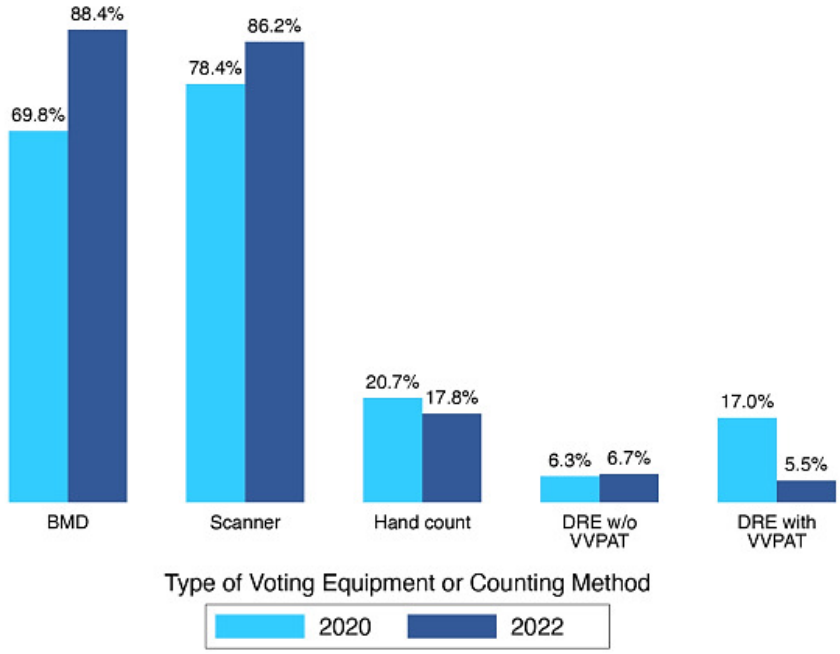


Figure 9. Technology used in the 2020-2022 US elections.

Source: https://www.eac.gov/sites/default/files/2024-11/2022_EAVS_Report_508c.pdf

The following are examples of devices currently used in the US elections (https://verifiedvoting.org/, 18.10.2024).

A Ballot Marking Device (BMD) allows voters to register their choices electronically by marking their votes without conducting automatic recounts. It displays a list of candidates on a touchscreen, where the voter selects and approves their choice. The machine then prints a paper ballot reflecting the selection.

An Optical Scanner is used to scan and automatically count votes cast on paper ballots. Voters mark their chosen candidate with a black pen and insert the ballot into the scanner, which scans it while placing it in the ballot box. At the end of voting, the scanner generates a report with the total number of votes cast.

A Direct-Recording Electronic (DRE) device, often referred to as a portable election computer, enables voters to cast votes on a touchscreen. After the vote is recorded, the system stores it in its internal memory and generates a Voter Verified Paper Audit Trail (VVPAT), allowing voters to confirm their selection via a paper receipt. This receipt is stored in a dedicated ballot box for potential audits.

In the DRE variant without VVPAT, voters also cast votes electronically, but no paper confirmation is generated. Votes are recorded and counted electronically.

4.5. The technological challenges of electoral processes

The introduction of technology into electoral processes is a key challenge in modern democratic systems. The dynamic development of technological tools and their increasingly widespread use in various aspects of social life have also affected the organization and

implementation of national elections are organized and conducted. This process, involving both technological evolution and the analysis of its impact on the functioning of electoral systems, requires a multidimensional approach that considers efficiency, cost, security, accessibility, and public trust.

As part of Kwidzinski (2024) proposes several technological solutions to the problems identified in the survey. Based on the previously performed analyses, a streamlined voting process using technology was designed for the four variants. Each of these presents the devices and their use, sequence of actions to be performed by the voter, and costs associated with designing and equipping the polling station. Kwidzinski also presented a prototype voting app that can replace the paper ballots used to date. The voting results were determined using an electronic balloon box, which could replace the current version and would be operated by the DEC chairman or his deputy. The costs associated with designing, equipping polling stations, and implementing the solution at all polling stations are included in the breakdown of all options. This section presents one such option.

4.6. Proposal for an improved electoral process using modern technology

The following is a proposal for an enhanced voting process in which the user's identity is verified using a biometric gateway and a fingerprint scanner. The vote in the election was cast via touchscreen on the voting machine, and the cast vote in the form of a digital ballot was placed and automatically calculated in the electronic balloon box.

4.6.1. Proposal of technologies to be used

- **Biometric gate** - the first stage of voter identity verification,
- **voting machine**, whereby a voter can vote in an election. This version of the device was equipped with a fingerprint scanner and digital ballot printer,
- **fingerprint scanner** - second stage of identity verification,
- **digital ballot printer** The printed digital ballot contains a unique barcode, which is a summary of the vote cast on the voting machine,
- **the electronic balloon box** acts as a traditional ballot box in which the voter inserts a previously received digital ballot. After appropriate authentication by the scanner, the electronic balloon-box confirms the vote.

4.6.2. Details of the technological solution

A storyboard depicting the sequence of actions performed during the voting process in elections organized by the NEC was designed. The storyboard presented (Figure 10) illustrates the proposal for an improved voting process according to Kwidzinski's variant A (2024).

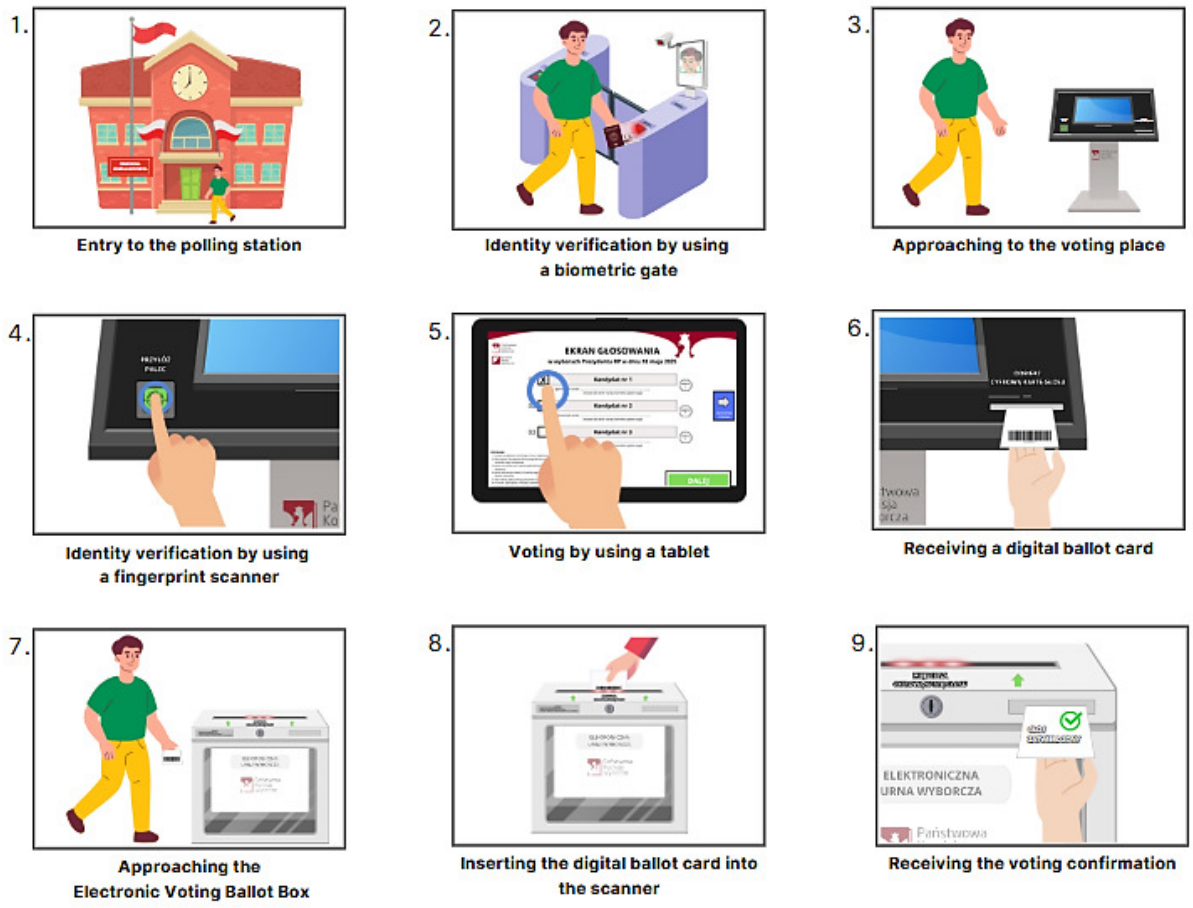


Figure 10 Improved voting process – storyboard.

Source: Kwidziński (2024).

Identity verification was performed in the proposed solution using a biometric gateway and fingerprint reader. The user then votes using a voting device and a touchscreen. After voting, the voter goes to the electronic balloon box where the voting process is completed.

4.6.3. Improved election process

Figure 11 shows a process diagram of the actions performed by voters when casting their votes at the polling station using the proposed technological solutions.

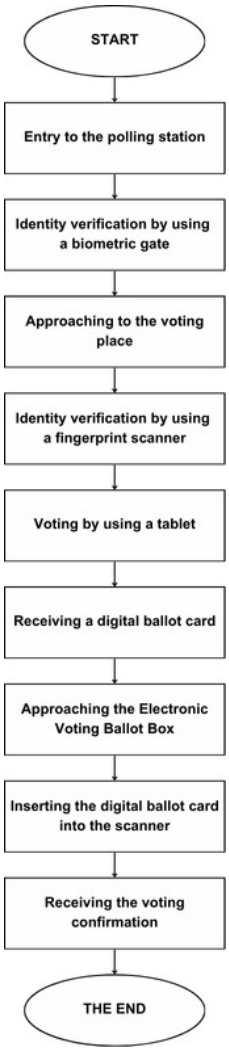


Figure 11. Improved process diagram voting

Source: own elaboration.

Upon entering the polling station, the voter prepares an identity document (e.g., e-card, passport, or QR code via the mCitizen app) and proceeds to the biometric gate. The document is scanned, and the voter's face is verified via a camera. Once matched, the gate opens, and the voter moves to the voting booth. Before accessing the voting tablet, the voter's identity is re-verified using a fingerprint reader. The tablet then activates, allowing the voter to select a candidate and confirm their choice. Afterward, a digital ballot is printed, which the voter inserts into a ballot scanner. Upon verifying the authenticity of the digital ballot, the system prints a confirmation, signaling the end and validity of the voting process.

Based on the survey, according to DEC members, the current process of tallying the results of the vote and drawing up the minutes is time-consuming. The amount of time spent tallying the results of the vote is a result of mistakes made and the incomprehensibility of the various steps in the preparation of voting records by commission members. The proposed solution reduces the scope of human intervention in favor of technology. A system operated by only one or two people - the committee chairman or deputy - is responsible for counting votes, taking minutes, and reporting results. By reducing the number of people responsible for determining

the results of the vote and entrusting the counting process to machines rather than committee members, the risk of errors is minimized. Manual counting of paper ballots, which takes several hours, will be replaced by computerized counting. Operating the machines together with downloading the voting report will take an estimated one–five minutes. In addition, to reduce the costs associated with the organization of elections, it was proposed to implement the solution not in every polling station in Poland but only in the polling stations located in the 100 most populated cities in Poland. The costs associated with implementing the solution at some polling stations were 80% lower than those associated with implementing the nationwide solution.

4.6.4. Cybersecurity of elections

Cyber security is about protecting, preventing damage to, and restoring the functioning of computers, electronic communication systems, and services, as well as wired and wireless communications, and the information they contain to ensure their confidentiality, integrity, availability, authentication, and non-repudiation (NIST, 2020).

Electronic voting (e-voting) is a method of voting in elections that uses various devices or technological solutions to register votes or the process of counting them. It can occur in two ways: stationary at the polling station or via the Internet. At the polling station, the voter votes using devices equipped with software that allows voter registration, authentication, voting, and the determination of voting results in a digital form. The objects of e-voting include mobile devices, kiosks, and computers (Taş, Tanrıöver, 2020). The second variant of e-voting is remote voting via the internet. It allows voting from anywhere (outside the polling station), and in some cases, it is possible to vote outside the country (Al-Ameen, Talab, 2013).

According to the Swiss Federal Chancellery (2024), the security of electronic voting relies on key principles such as verifiability to detect manipulation through cryptographic methods, shared responsibility by dividing the system into subsystems with limited internet access, and transparency by publishing source code for external analysis. Public scrutiny, including "bug bounty" programs, engages users to report vulnerabilities, while continuous updates and independent examinations by experts ensure systems meet current technical standards and function securely.

5. Discussion and conclusion

The analysis of electoral processes and voter turnout in Poland over the period 2000-2024 provides a number of valuable conclusions that can serve as a foundation for planning future activities in the area of improving electoral systems. The results of this research indicate the dynamic development of civic involvement in key votes, such as parliamentary and presidential elections, with the simultaneous challenge of low turnout in elections to the European

Parliament and referenda. In addition, a survey of DEC members confirmed the need to implement modern technologies for vote counting. The most problematic stages of the electoral process identified by the DEC members were activities related to determining the results of the vote and drawing up protocols. These activities are not only time-consuming, but also prone to errors, indicating the need to improve them.

One of the key challenges is the adequate preparation of election commissions. The results of the analysis of training materials indicate that, despite the availability of detailed guidelines, some procedures remain difficult to understand and require additional support, especially in the context of using new technologies.

Digital technologies that can increase the efficiency and security of elections are an important direction in the discussion of the future of electoral processes in Poland. Surveys indicate that digitization, including the automation of vote counting, the introduction of electronic systems for minutes, and the use of biometrics for voter verification, are solutions desired by both commission members and experts involved in electoral processes.

In conclusion, it is necessary to strive for further optimization of electoral processes, which requires an integrated approach that considers citizens' needs, legal requirements, and technological possibilities. The proposed innovations should be tested on a limited basis to assess their effectiveness and public acceptance before full implementation. Thus, Poland can become a leader in modern, efficient, and transparent elections, meeting the challenges of the 21st century.

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PERCEIVING THE BIOECONOMY: POLARIZED CONSUMER ATTITUDES IN POLAND

Małgorzata PINK

University of Agriculture in Krakow; malgorzata.pink@urk.edu.pl, ORCID: 0000-0002-3390-4140

Purpose: The purpose of this article is to understand the dynamics of the consumer market for bioeconomy products and to answer specific questions: How do consumers understand the bioeconomy and its products, ae they ready for them? What consumer characteristics shape their perception of the bioeconomy? What, in the opinion of consumers, should be the role of legislators in implementing bioeconomy principles?
Design/methodology/approach: The study was conducted in Poland in 2024/2025 using computer-assisted telephone interviews. The study sample included 500 adults from the general population. Data were collected using a questionnaire containing nine single-choice Likert-scale questions and one multiple-choice question. Data were analyzed using statistical tests such as association rule analysis, Student's t-test, Pearson correlation test, ANOVA, and the k-means algorithm using the elbow method. Analyses were performed using the DATATable application.
Findings: The results revealed a high level of recognition of the term 'bioeconomy', alongside traditional associations, indicating a non-innovative perception of the concept. Consumers are polarized into enthusiasts and sceptics, reflecting the broader trend of socio-political polarization. Income and familiarity with the bioeconomy were the key factors shaping responses: higher income correlated with greater openness to bio-based products and stronger expectations of regulation, while familiarity had a similar effect. Consumers are prepared for implementation, but legislators must promote bioeconomy, empower its awareness, set standards, while addressing the risks its politicization.
Research limitations/implications: The study conducted has its limitation, especially in the context of the composition of the research sample. The sample could not be selected based on quotas due to the lack of consent from potential respondents.
Originality/value: European research lacks detailed analyses of consumer attitudes. There is little empirical research in this area in Central and Eastern Europe. There is also a gap in research defining the role of legislators in the context of consumer expectations regarding the implementation of sustainable bioeconomy principles.
Keywords: bioeconomy, consumers, bio-based products, perception, expectations towards the legislator.
Category of the paper: Research paper.

1. Introduction

In 2012, the bioeconomy became one of the European Union's key strategies. It highlighted the importance of using biological resources to address social, economic and environmental challenges. In the 2018 strategy update (COM (2018) 673/2) clarified the understanding of bioeconomy as a use of renewable biological resources on land and sea, such as crops, forests, fish, animals and micro-organisms, for the production of food, materials and energy. The basic principle is to adhere to a sustainable approach to the production of biomass and bio-based products, as emphasised in the title of the document: *A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment* (EC 2018). EU strategy defines goals, compliant with Sustainable Development Goals: to substitute fossil resources; ensure the sustainable production and use of biomass, integrating circular economy principles to minimize waste and maximize resource efficiency; strengthen the connection between the economy, society, and the environment; aiming for inclusive growth, rural development, and ecosystem preservation on the base of innovation and competitiveness (De Besi, McCormick, 2015; Ronzon, Sanjuán, 2020).

Stakeholders engagement and communication are key to implementing innovative bioeconomy solutions, but innovation in certain bioeconomy sectors requires a clear and coherent regulatory framework, customer and market acceptance of new technologies and bioproducts, and stakeholder-led initiatives for sustainable development (Aguilar *et al.,* 2019). The research highlights the importance participatory governance, which means multi-level, proactive involvement of stakeholders (D'Amico *et al*., 2022), need for education and communication and social acceptance (Papadopoulou *et al.,* 2022). These conditions are often difficult to meet. Stakeholder cooperation and commitment to sustainable development are eroding as a result of the increasingly pronounced polarization of highly developed societies. The increasing polarisation in Western societies marks a fracture in society. Political ideology and party affiliation are among the strongest predictors of environmental sustainability perceptions and related behaviours. Numerous studies, primarily conducted in the USA, have shown that conservatives are more sceptical of climate change, less inclined to combat its causes than their more liberal counterparts. This is evident in values and norms related to sustainability, where Democrats demonstrate significantly higher pro-environmental values and norms, while Republicans demonstrate a greater lack of understanding, attribute less importance to climate change, and reveal less understanding of the importance of sustainable behaviour (Casper *et al*., 2021). Although European Union society is different from the USA, it is also experiencing polarization, which may translate into attitudes supporting or inhibiting sustainable development (Donat *et al*., 2025). Meanwhile, the success of the bioeconomy in the EU is important for its economy, supporting growth, jobs, sustainability, and strategic policy goals. Bioeconomy is expected to play an important role in the low carbon economy of the

EU by 2050, with a current market of about EUR 812 billion in value added and employing 17.2 million people (EC, n.d). The development of the bioeconomy is an opportunity for the Polish economy, which has a potential for biomass production. Poland produces approximately 10% of the EU's total biomass annually and stands above the EU average in terms of employment in biomass-producing sectors and agriculture, which is the largest sector in the bioeconomy, accounting for 65% of the workforce. In terms of turnover and value added, Poland exceeds the EU average in sectors such as agriculture, forestry, food, beverages and tobacco, liquid biofuels, paper production, and wood products and furniture, making it the fourth largest furniture exporter in the world (Loizou *et al*., 2019). The bioeconomy has been identified as a potential key sector of the Polish economy and a smart specialization in numerous regions of Poland (Nowak *et al*., 2022). However, the cited studies also point to a number of structural barriers, such as dependence on traditional sectors, but also the lack of a national bioeconomy strategy, unsatisfactory levels of R&D funding, no cooperation among bioeconomy stakeholders and low public awareness (Chmieliński, Wieliczko, 2022).

In EU, there is still little research on consumer attitudes toward bioeconomy products, especially with regard to industrial products. The context of sustainable food production is much more deeply ingrained in the minds of consumers and researchers, due to years of efforts to promote organic food in the EU. Existing research indicates that consumers in European countries are rather open to the adoption of bio-based products (Gaffey *et al*., 2021; Morone *et al.,* 2021; Sijtsema *et al.,* 2016; Kymäläinen *et al.,* 2022), but the associations with bio-based products among consumers are not always unequivocally positive. Studies have found there to be a lack of consumer knowledge and awareness (Fernández *et al.,* 2023). Others have revealed citizens' concerns regarding the possible negative socio-economic effects of the transition to the bioeconomy, including higher prices of products, a decrease in quality of life and greater social inequity (Zander *et al.,* 2022; Stern *et al.,* 2018). Consumer attitude studies often focus on specific products (Gatto, Re, 2021), e.g. biogas, (Herbes *et al.,* 2018; Kulla *et al.,* 2022), algae-based goods (Araújo *et al.*, 2021) or bioplastic (Filho *et al.,* 2021). Despite fragmented studies in various EU countries a noticeable research gap exists. In Poland, there is little empirical research, and existing studies often focusing on organic food or renewable energy sources, rather than the broader understanding of the bioeconomy. Research on bioeconomy products is conducted outside the context of the concept and systemic meaning of the bioeconomy. Consumers relate to a specific product, but beyond the phenomena of cascading, circularity, or sustainability. There is also lack research that would define the role of the legislator in the context of consumer expectations regarding the implementation of the sustainable bioeconomy. In this context, the purpose of this article is to answer the following questions:

- How do consumers understand the bioeconomy and its products?
- What consumers' characteristics shape their perception of the bioeconomy?
- What, in the opinion of consumers, should be the role of the legislator in implementing the principles of bioeconomy?
- Are the consumers ready for bioeconomy products?

2. Materials and methods

The research was conducted in Poland in 2024/25 by telephone interviewing survey of a sample of adults taken from the general population. The sample size was n = 500, adopted based on the formula:

$$Nmin = \frac{N_P(\alpha^2 \cdot f(1-f))}{N_P \cdot e^2 + \alpha^2 \cdot f(1-f)}$$

Nmin – min. sample size,

Np – size of the general population,

α – confidence level,

f – fraction size,

e – maximum error.

In '24, Poland's population was 36.55 M (World Bank Open Data, n.d.). The fraction size was assumed to be 0.5, and the maximum error - 5%. The minimum sample counts 384 individuals. The sampling method was simple and probabilistic,. The structure of the survey sample is shown in the Annex 1.

Respondents answered 9 single-choice questions on the Likert scale and 1 cafeteria question (see Annex 1).

Answers to the cafeteria question, containing options of phenomena which the respondent associates with the bioeconomy were analysed using market basket analysis with association rules. This method was created to identify patterns in customer purchase behaviours (Aguinis *et al.,* 2013), but may be applied in fields outside of the scope of marketing, to discover patterns in large datasets (Szymkowiak *et al*., 2018).

An analysis of the correlation between the obtained variables describing attitudes and demographic variables, was run using the following tests: 1) t-test, for the variable *gender*; 2) Pearson's correlation test for the variables: *age* and *net income p.c. in the household*; 3) ANOVA for the variables: *place of residence*, *education*, *familiarity with the term 'bioeconomy'*.

Clustering of the survey sample was carried out using the k-means algorithm. Its purpose is to partition the dataset into distinct clusters. In doing this, the algorithm seeks to ensure that data points in the same cluster show a high degree of similarity, while maintaining noticeable differences from those in other clusters. The optimal number of clusters was determined based on the elbow method, which consists of finding a point in the list of preference values up to which the number of clusters increases slightly with increasing values, and from which the number of clusters begins to grow rapidly even with small changes. All analyses were performed in the DATATable. In the context of researching attitudes towards bioeconomy goods, the following were taken into account: sustainable food goods, using the example of organic food and selected industrial goods.

3. Results

3.1. Understanding of the 'bioeconomy' concept

Nearly one in every two consumers declared themselves to be familiar with the term *bioeconomy* (Figure 1).

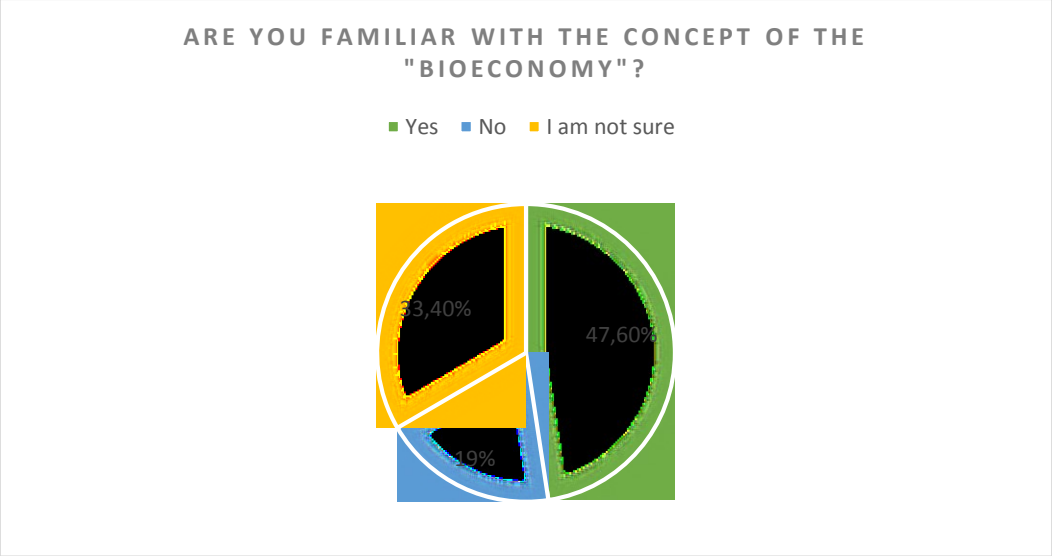


Figure 1. Familiarity with the term *Bioeconomy*.

A majority of consumers did have associations with the bioeconomy. Most frequently, respondents cited biomass (59%), biofuels (47%), organic farming (42%) and biotechnology (41%). Majority of the associations included the prefix -bio. Many consumers also associated the bioeconomy with organic agricultural production. Relations between the frequency of declaration of specific associations are shown in schematic form in Figure 2.

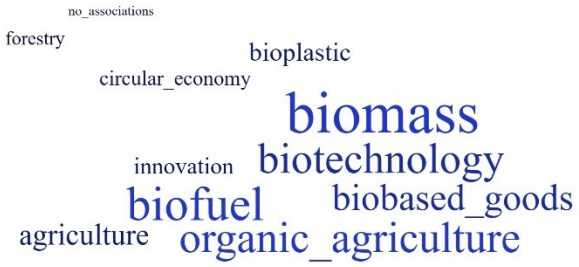


Figure 2. Word cloud of associations with the term *Bioeconomy.*

Associations with the bioeconomy were subjected to an association rule analysis, the results of which are presented in Table 1.

Table 1.
Association rule analysis

Lhs	Rhs	Frequency	Support	Confidence	Lift
Biomass, Organic farming	Biofuels	78	0.16	0.89	1.87
Biomass, Biotechnology	Biofuels	97	0.19	0.87	1.83
Bioplastics	Biofuels	98	0.2	0.84	1.77
Biomass	Biofuels	159	0.32	0.82	1.74
Biotechnology, Organic farming	Biofuels	83	0.17	0.81	1.72
Biofuels, Biotechnology	Biomass	97	0.19	0.7	1.81
Biofuels, Organic farming	Biotechnology	83	0.17	0.69	1.69
Bioplastics	Biotechnology	80	0.16	0.68	1.67
Biotechnology	Biofuels	139	0.28	0.68	1.43
Biofuels	Biomass	159	0.32	0.67	1.74
Biofuels, Organic farming	Biomass	78	0.16	0.65	1.68
Bioplastics	Biomass	76	0.15	0.65	1.68
Agricultural production	Organic farming	88	0.18	0.64	1.52
Biomass, Biofuels	Biotechnology	97	0.19	0.61	1.49

Respondents who link the bioeconomy to biomass and organic farming often also mention biofuels. The technological dimension of biomass processing (biotechnology) is strongly associated with bioenergy, and the bioplastics are seen as part of the same sustainable package as biofuels. The most frequently repeated association is the combination: biomass – biofuels, revealing the understanding of biomass as a raw material for the production of biofuels. High lift indicates that the occurrence of Rhs (e.g. *biofuels*) is much more likely when the appropriate associations (Lhs) appear. Respondents do not treat these concepts as independent, they see them as strongly semantically related. Bioeconomy is perceived as an energy and raw material system, which is visible in the context of the dominance of associations with biofuels and biomass. This indicates a functional, production and processing understanding of bioeconomy. A visible role of technology - the presence of biotechnology and bioplastics - suggests that consumers recognize modern components of bioeconomy, although they may not understand their details. There is a weaker disclosure of the socio-cultural or innovative aspect, a lack of associations with the circular economy or innovation, which indicates a limited understanding of bioeconomy as a systemic transformation.

3.2. Consumer perception of bioeconomy products

Respondents answered 8 questions determining their attitudes to bioeconomy products and expectations upon legislators regarding the implementation of bioeconomy solutions. The answers were rated on a 5-point Likert scale. The distribution of answers was normal for all questions. The purpose of this part of the study was to determine differences in consumer attitudes depending on the demographic characteristics and declared level of familiarity with the bioeconomy concept. Consumers' answers to questions related to organic food are presented in Figure 3.

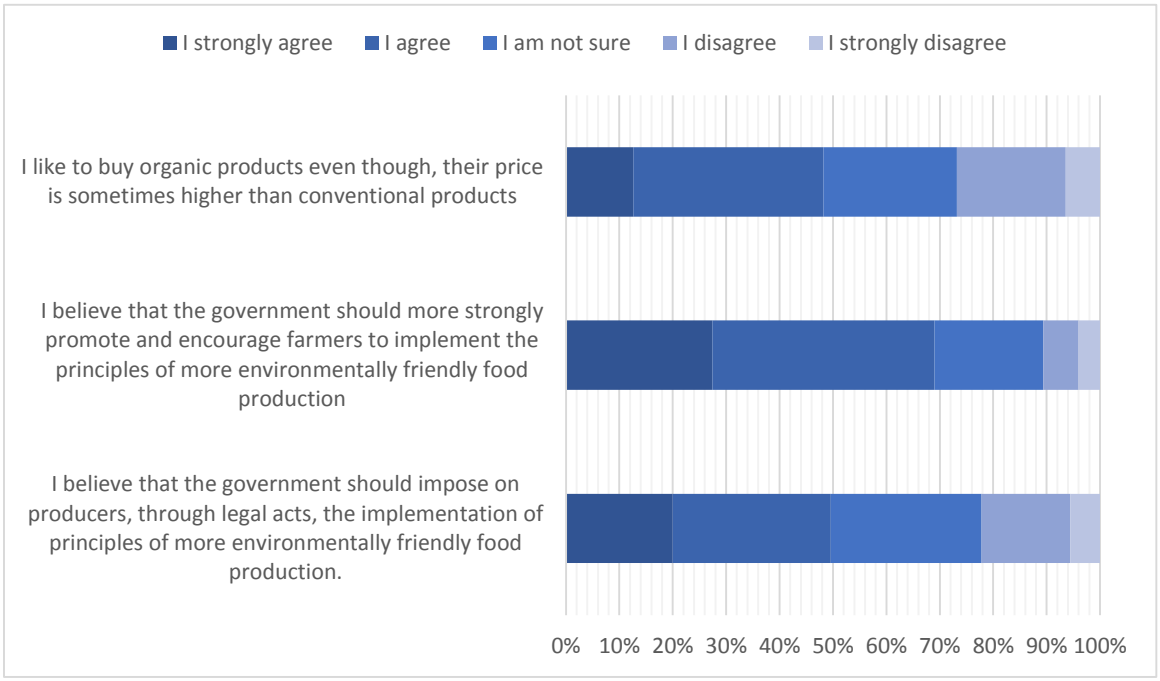


Figure 3. Perception of sustainable food and expectations upon legislators.

48% of the consumers have a positive attitude to the organic food. Nearly 70% expect that the legislators should promote environmentally friendly food production and nearly 50% that it should impose the production standards on producers through legal frameworks.

Answers to questions concerning industrial bio-based products are presented in Figure4.

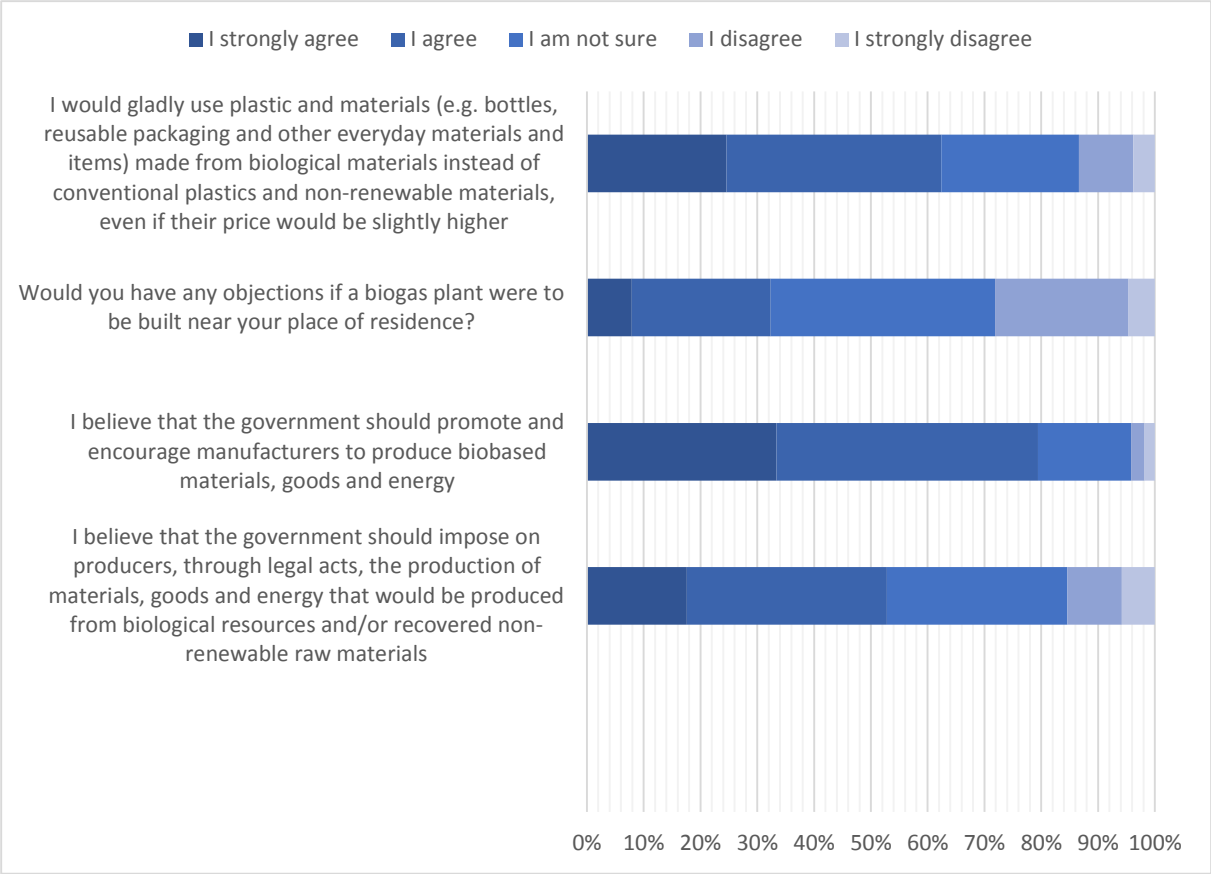


Figure 4. Perception of industrial bio-based products and expectations upon legislator.

The vast majority of respondents declared themselves to be open to industrial bio-based products. Despite this, consumers still have strong prejudices against biogas plants, with only around 28% of respondents not having anything against the construction of such infrastructure near their place of residence. In relation to industrial production, expectations regarding the legislator's activity in the context of promoting and imposing rules of cleaner production are even clearer than in the case of food. Around 80% expect legislators to be active in promoting bio-based goods, while over 50% expect that these issues to be regulated institutionally by orders and prohibitions as appropriate

The distribution of answers concerning opinions about bio-based materials is shown in Figure5.

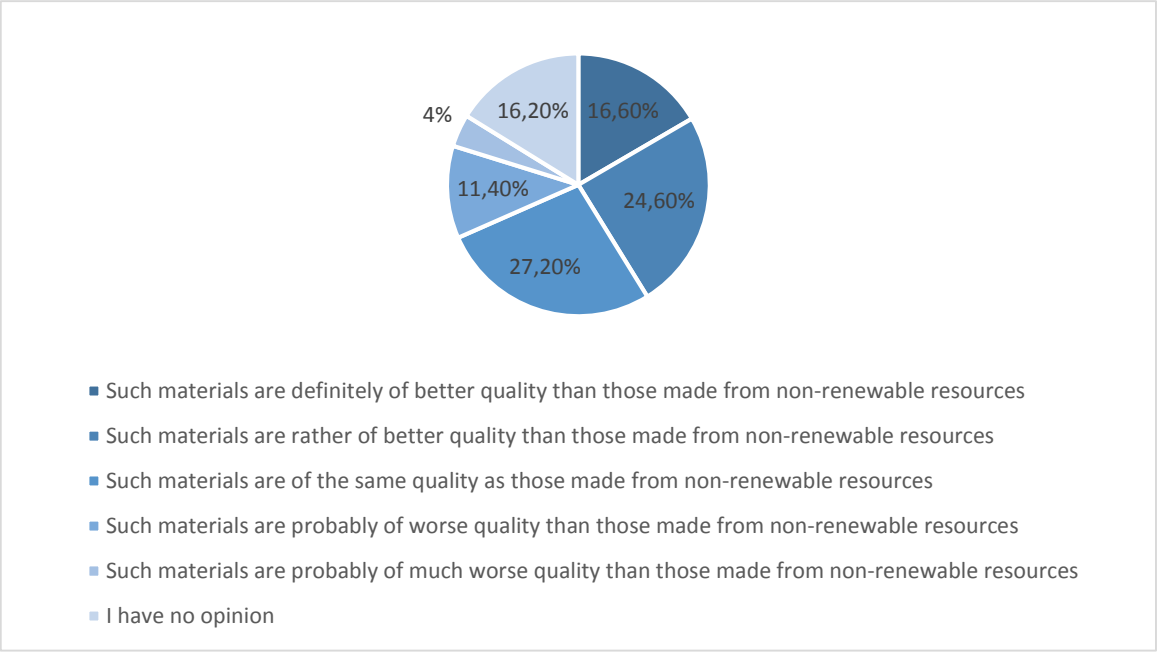


Figure 5. Opinions about industrial bio-based materials.

Most consumers have positive opinions about the quality of bio-based products. Around 15% of respondents believe them to be of worse quality than from non-renewable resources, while over 16% say they have no opinion.

In the next step, the data underwent statistical analysis to determine the relationship between answers and demographic characteristics (Table 2).

Table 2.
Correlation between demographic characteristics and declared familiarity with the term 'bioeconomy' and responses to questions about attitudes, perceptions and expectations in the area of bioeconomy goods

Q	Question	Gender	Age	Place of residence	Education	Net income p.c. in the household	I am familiar with the concept of the ***bioeconomy***
	Type of statistical test	t-test	Pearson correlation test	ANOVA	ANOVA	Pearson correlation test	ANOVA
	Null hypothesis:	*There is no difference between groups 1 and 2 with respect to the dependent variable*	*There is a correlation between the age and correspondin g variables*	*There is no difference between the 6 categories of the independent variable 'place of residence' with respect to the dependent variable*	*There is no difference between the 4 categories of the independent variable 'level of education' with respect to the dependent variable*	*There is a correlation between net income per capita and correspondin g variables*	*There is no difference between the 3 categories of the independent variable 'I am familiar with the concept of the bioeconomy' with respect to the dependent variable*

Cont. table 2.

1	*I like to buy organic products even though, their price is sometimes higher than conventional products*	The null hypothesis was not rejected	The correlation is statistically insignificant r(498) = -0,04, p = 0,345	F = 1.17, p = .325, the null hypothesis was not rejected	F = 1.66, p = .175, the null hypothesis was not rejected	The correlation is statistically insignificant, r(498) = -0.07, p = .103	F = 23.63, p = <.001, the null hypothesis was rejected
2	*I believe that the government should more strongly promote and encourage farmers to implement the principles of more environmentally friendly food production*	The null hypothesis was not rejected	The correlation is statistically insignificant r(498) = -0.09, p = .051	F = 1.5, p = .189, the null hypothesis was not rejected	F = 1.8, p = .146, the null hypothesis was not rejected	The correlation is statistically significant, r(498) = -0.11, p = .018	F = 3.73, p = .025, the null hypothesis was rejected
3	*I believe that the government should impose on producers, through legal acts, the implementation of principles of more environmentally friendly food production*	The null hypothesis was not rejected	The correlation is statistically insignificant r(498) = -0.08, p = .077	F = 1.2, p = .308, the null hypothesis was not rejected	F = 0.98, p = .402, the null hypothesis was not rejected	The correlation is statistically significant, r(498) = -0.1, p = .029	F = 2.72, p = .067, the null hypothesis was not rejected
4	*I would gladly use plastic and materials (e.g. bottles, reusable packaging and other everyday materials and items) made from biological materials instead of conventional plastics and non-renewable materials, even if their price would be slightly higher*	t(474.76) = -3.06, p = .002, 95% confidence interval [-0.48, -0.1], the null hypothesis was rejected	The correlation is statistically significant r(498) = -0.12, p = .01	F = 1.22, p = .301, the null hypothesis was not rejected	F = 0.21, p = .887, the null hypothesis was not rejected	The correlation is statistically significant, r(498) = -0.1, p = .03	F = 7.86, p = <.001, the null hypothesis was rejected
5	*Opinion on the quality of biobased material (not analysed statistically)*						
6	*Would you have any objections if a biogas plant were to be built near your place of residence?*	t(498) = -2.76, p = .006, 95% confidence interval [-0.42, -0.07], the null hypothesis was rejected	The correlation is statistically insignificant r(498) = 0.06, p = .213	F = 0.27, p = .931, the null hypothesis was not rejected	F = 1.98, p = .115, the null hypothesis was not rejected	The correlation is statistically insignificant, r(498) = 0.03, p = .475	F = 0.19, p = .823, the null hypothesis was not rejected
7	*I believe that the government should promote and encourage manufacturers to produce biobased materials, goods and energy*	The null hypothesis was not rejected	The correlation is statistically insignificant r(498) = -0.08, p = .075	F = 0.61, p = .693, the null hypothesis was not rejected	F = 5.32, p = .001, the null hypothesis was rejected	The correlation is statistically significant, r(498) = -0.1, p = .026	F = 8.59, p = <.001, the null hypothesis was rejected

Cont. table 2.

8	*I believe that the government should impose on producers, through legal acts, the production of materials, goods and energy that would be produced from biological resources and/or recovered non-renewable raw materials*	The null hypothesis was not rejected	The correlation is statistically insignificant r(498) = -0.06, p = .214	F = 2.77, p = .018, the null hypothesis was rejected[1]	F = 0.57, p = .636, the null hypothesis was not rejected	The correlation is statistically significant, r(498) = -0.11, p = .013	F = 3.26, p = .039, the null hypothesis was rejected

The null hypotheses posited to be no differences in individual demographic characteristics and no correlation between demographic characteristics and attitudes to the bioeconomy. In the majority of cases, these hypotheses were verified. In certain cases, the hypotheses were rejected. The gender of respondents proved to be a differentiating factor in attitudes concerning readiness to purchase products made from bio-based materials and the location of biogas plants near to their place of residence. The average value of answers for Q4 for group 1 (women) in this sample is 2.16, while it is 2.45 for group 2 (men). It means, women were more willing to use bio-based products. The average value of answers for the Q6 for group 1 in this sample is 2.83, while it is 3.08 for group 2[2], which means that women would be less likely to accept a biogas plant near to their place of residence.

The age of respondents resulted in a differentiation in attitudes in 1 case. The result of the Pearson correlation showed that there was a low, negative correlation between answers for Q4 and respondents age group. This means that younger consumers would be less enthusiastic about buying products made from bio-based materials. This correlation is however a weak one.

Level of education differentiated the surveyed population in their answers to Q7. The $\eta 2 = 0.03$ suggests a small to medium effect size. The Bonferroni post-hoc test revealed that the pairwise group comparisons of 4 (higher education) – 2 (vocational) and 2-3 (secondary education) have a p-value less than 0.05 and thus, it can be assumed that these groups were each significantly different pairwise. The means and standard deviations are provided in Table 3.

[1] With reference to an analysis of the significance of place of residence, the null hypothesis was rejected for Q6. The ANOVA test showed that there was a significant difference. However, a Bonferroni Post hoc test proved no pairwise group comparison was significant; all p values were greater than 0.05. It should therefore be concluded that, for the survey sample, there is no interdependence between the place of residence of the consumers and their perception of bioeconomy products or opinions regarding the role of the legislator in shaping cleaner production and consumption policies.

[2] In the case of answers to that question, a reverse Likert scale was used. Lower values indicate that the consumer was opposed to the construction of a biogas plant near to their place of residence, while a higher values means they would not have anything against it.

Table 3.
Means and standard deviations for answers (Q7)

Groups according to education	**1**	**2**	**3**	**4**
Means and standard deviations for answers to *I believe that the government should promote and encourage manufacturers to produce biobased materials, goods and energy*	2.57/1.13	2.31/0.94	1.92/0.87	1.84/0.81

The higher the level of education, the stronger the expectation is for the legislator to implement a policy to promote the bioeconomy.

The demographic variable according to which the answers of respondents were most frequently differentiated proved to be net income p.c. The results of the correlation test showed there to be statistically significant, though very weak or weak correlations with the answers for Q2, Q3, Q4, Q6, Q7. This means that with an increase in the income of the respondents, they have higher expectations that the legislator will be active in encouraging more sustainable productions of foods and bio-based goods and in taking regulatory measures to impose transformation upon producers. The test also revealed a greater readiness to consume bio-based materials together with an increase in the level of income. The research showed the significance of the declared level of familiarity with the term *bioeconomy* for the perception of its products and expectations upon the legislator (Q1, Q2, Q4, Q7, Q8). Table 4 presents the results of the Bonferroni test and the means and standard deviations, which allow the direction of differences in the specific groups to be determined.

Table 4.
Bonferroni test and the means and standard deviations for answers to selected questions and the independent variable of net income per capita in the household

	Bonferroni Post-hoc test	**Mean/St.dev 1**	**Mean/St.dev 2**	**Mean/St.dev 3**
Q1	1 – 3, 1 – 2, 3 – 2	2.41/1.06	2.86/1.04	3.26/1.14
Q2	1 – 2	2.07/1	2.22/1.03	2.4/1.11
Q4	1 – 2 and 3 – 2	2.16/1.01	2.3/1.03	2.66/1.16
Q6	1 – 2 and 3 – 2	1.8/0.78	1.95/0.87	2.23/0.97
Q7	1 – 2	2.41/1.05	2.52/1.05	2.74/1.12

The ANOVA showed that there were some significant differences between the answers of consumers with different declared knowledge level. A Bonferroni Post hoc test was used to compare the groups in pairs to find out which were significantly different. The Bonferroni Post hoc test showed that the pairwise group comparison p-value of less than 0.05, and thus, it can be assumed that the groups are significantly different. Based on the values of the means and standard deviations, one pattern is visible for all answers: people who declare that they are familiar with the term *bioeconomy* are more open to bioeconomy and have the highest expectation with regard to action on the part of the legislator, both in the area of its promotion and imposing transformation in its direction on producers.

The last step consisted of clustering of the surveyed population. The optimum number of clusters was determined using the elbow method (Figure 6).

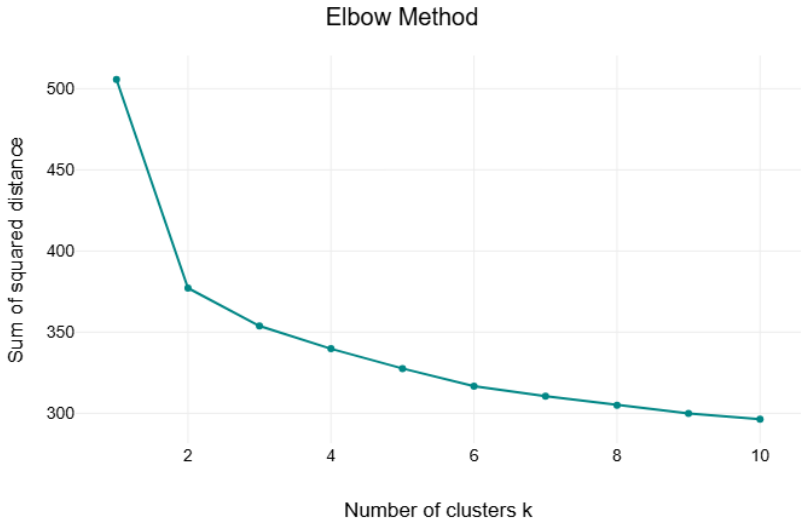


Figure 6. Elbow curve.

The break in the curve is visible at level 2. This means that the optimum number of clusters is 2. The averages for the individual clusters are presented in Table. 5.

Table 5.
Average answers to questions in clusters 1 and 2

Averages for:	**Number of respondent**	**Age**	**Income**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**
Cluster 1: *Sceptics*	228	3.08	3.38	3.35	2.83	3.31	3.03	3.98	2.78	2.39	3.18
Cluster 2: *Enthusiasts*	272	3.51	3.76	2.2	1.64	1.97	1.69	2.37	3.09	1.55	1.94

Sceptics are on average younger than the *Enthusiasts* and have lower incomes. *Sceptics* are characterised by a lower *level* of interest in bioeconomy products: On average, consumers do not opt for organic farming products and do not see any need for the promotion and regulation of this type of production by the legislator. They do not take any position on industrial bio-based products. They consider bio-based materials to be worse than conventional ones, and the presence of biogas plants near to the place of residence is met with moderate reluctance. At the same time, they do not have anything against the legislator promoting industrial bio-based materials and products. Imposing production methods is however perceived indecisively with a tendency towards rejection. The *Enthusiasts*, among who the average age and incomes are slightly higher, are characterised by the opposite point of view. They are consumers of organic food who support action on the part of the legislator in the context of both promotion and the creation of legal frameworks to incentivise producers. They are open to industrial bio-based products, though on average they are undecided on the issue of biogas plants. They expect government to promote and regulate industrial bio-based products.

4. Discussion

4.1. Understanding of the bioeconomy

Knowledge about consumer attitudes and awareness in relation bioeconomy products in Europe is scattered and limited. Consumers from Finland have a positive image of the bioeconomy (Vainio *et al.,* 2019). Swedish studies focus on the Forest-Based Economy and wood construction proves their acceptance by consumers (Nagy, Berg Rustas, Mark-Herbert, 2021). Respondents in Austria had differing opinions about the bioeconomy (Stern *et al*., 2018) and in Germany, though familiarity with the concept is low, the underlying values of the bioeconomy are shared by consumers (Dallendörfer *et al.,* 2022). In this study, consumer perception of the bioeconomy is ambiguous. Nearly half of respondents say they were familiar with the concept of the *bioeconomy*. The associations with the *bioeconomy* proves that consumers associate this concept mainly with biomass and biofuels and with organic food (which in Poland is frequently referred using colloquial term *bio*). It can thus be assumed that consumers' associations are based on semantics and are not necessarily the result of deeper knowledge. Consumers associate the bioeconomy with circularity or innovation, or even with primary production, only to a very limited extent, which proves that, even if this concept is actually starting to play an active part of public consciousness, it is not yet embedded in broader socio-economic contexts. The bioeconomy is not seen as a direction for systemic change, but as a source of possible substitutes for conventional products. An association rule analysis showed that, most frequently, people who associated the bioeconomy with biomass and organic farming, also added biofuels to the list. Associations with biomass and biotechnology meant there was a high chance that the choices of those consumers would also include biofuels. The combination in the basket of a single consumer of biomass and biofuels was after all the most frequently chosen set of associations occurring in the case of over 30% of respondents. Respondents perceive biofuels to be a central element of the bioeconomy. This is understandable, given that the topic of biofuels has been a subject of social discussion since the 1990s, when biofuels started to be produced from rapeseed (cf. Grzybek, 1996; Olejniczak, Adamska, 1999). At that time, there was also a short-lived boom in the cultivation of energy willow (cf. Rozanowski, 1993; Stecyk, 1995). This topic had time to take root in the consciousness of consumers, as did the topic of organic food. At the same time, respondents turned out to strongly distance themselves from the use of biomass for the production of biogas. Only 28% of respondents did not express any doubts concerning the presence of a biogas plant near to their place of residence. So, while biofuel plays an important part the respondents' associations, they tend to be sceptical with regard to biogas. The majority of respondents (over 60%) demonstrate an open attitude toward bio-based materials, which makes them similar to other European consumers. This is a larger proportion than those declaring they consume organic food, which constituted less than half. It is important to emphasize that bio-based

industrial products—bioplastics and biocomposites—although present on the market, are new to consumers. Therefore, the question asked about hypothetical willingness to consume them was asked about actual consumer habits.

4.2. What consumers' characteristics shape their perception of the bioeconomy?

Sustainable consumer attitudes are shaped by numerous factors. Values, such as ecological awareness, social responsibility and moral attitudes play a key role in shaping the intentions of consumers concerning the purchase of sustainable products. Many studies look for the source of environmentally friendly behaviours in culture. For example, greater power distance (The Culture Factor, n.d.) may lead to a decreased feeling of personal responsibility for committing to pro-social and pro-environmental behaviours. In cultures, with higher distance to power, individuals may feel less entitled to question the status quo or to demand that corporations adopt sustainable practices, which leads to passive acceptance of unsustainable behaviours (Winterich, Zhang, 2014). One cultural characteristic shaping pro-environmental models of consumption is motivation towards achievement and success (formerly femininity vs. masculinity, The Culture Factor, n.d.). Research conducted by Brough et al. indicates that, in masculine cultures, eco-friendly products may be perceived as less desirable or even *unmanly*, which may discourage consumers from committing to sustainable consumption (Brough *et al.,* 2016). Consumer attitudes are also shaped by the institutional environment, and one important factor appears to be political views. Studies indicate that consumers who tend to the political left are more likely to demonstrate commitment on sustainability issues, adopt pro-environmental attitudes, and show greater concern for the social good. Consumers with liberal views are more committed to political action than conservatives and are more attached to the values of sustainable development (Watkins *et al*., 2016). McCright and Dunlap have provided confirmation of political polarisation in the context of environmental attitudes. Analysing Gallup data, they found that liberal consumers are more pro-ecological than conservative consumers, and show that liberals and Democrats are more likely to report beliefs consistent with the scientific consensus on climate change and express greater personal concern about global warming than conservatives and Republicans (McCright, Dunlap, 2011). Although the study conducted did not include questions about values, it is also worth addressing elements of the institutional environment – culture and politics. In terms of power distance, Poland ranks among the countries in Europe with a higher power distance and a relatively strong motivation towards achievement and success (The Culture Factor, n.d.), which places the values of the country's population in an area of greater distance from the issue of environmental sustainability. The issue of political polarization also appears to be a significant factor shaping attitudes. The last decade has shown strong political polarization, dividing society into almost equal parts, represented by two main political parties – the conservative Law and Justice party (PiS) and the more liberal Civic Platform (PO). Although respondents' political views were not surveyed, perception of bioeconomy products and expectations upon legislator divided the

surveyed population into two clusters, clearly polarising consumers into the *enthusiasts* and the *sceptics*. This strong polarisation in the opinions of consumers has already been observed in relation to energy policy and is linked to the polarisation of worldviews in Polish society. The emotional and intellectual tension between the liberal and conservative camps is transferred to attitudes related to the approach to the natural environment and energy transformation. The issue of phasing out coal plays a role in public awareness as a factor antagonising entire social circles. Differences in the approach to renewable energy sources are reinforced by different views on moral issues and other dimensions of polarisation (Ruszkowski *et al.,* 2023). It can be assumed that the polarisation of opinions regarding the legislator's responsibility for implementing the bioeconomy and the attitude towards bioeconomy products constitutes an antagonising mechanism similar to those mentioned above.

Numerous studies focus on the impact of demographic characteristics – gender, age, economic situation and level of education – on consumer attitudes. Studies of consumers of food or clothing indicate that women are more open and willing to pay for more sustainable goods (Bulut *et al.,* 2017; García-González *et al*., 2020; Mandarić *et al.,* 2021). In a review article concerning perception of the circular economy, of which the bioeconomy is a part, it has been shown that women are more environmentally aware and more strongly inclined to opt for circular products. This same article found that younger consumers are characterised by a higher level of awareness, while older consumers are more likely to cooperate and participate in sharing and the collaborative economy. Strongly pro-environmental attitudes are characteristic of consumers with a higher level of education and income (Henriques *et al.,* 2023). The significance of higher income has been confirmed in numerous studies concerning food (Voráčová *et al.,* 2016; Schiano *et al.,* 2020), industrial products (Aliyev *et al.,* 2019) and luxury goods (Gasulla, Tortajada *et al.,* 2024). In the conducted study, demographic variables explain consumer attitudes to a limited degree and, in most cases, the statistical relationships detected are weak. Women in the survey sample proved to be more open to industrial bio-based products (except in the case of biogas plants) than men. The demographic characteristic by which attitudes were most strongly differentiated proved to be level of income. With an increase in income, there is an increase not only in openness to bio-based products, but above all in expectations upon those in government with regard to shaping of policy on bio-based goods and sustainable food production. Vaznonis et al. (Vaznonis *et al.,* 2024) argue that incomes levels may have an influence on pro-environmental attitudes. They are linked to a higher level of subjective well-being and being more ready to engage in pro-environmental behaviour. Similar conclusions were reached in a study by Capstick et al. (Capstick *et al.,* 2022). The study indicates that a higher income level may facilitate the transition to post-materialist values related to sustainable consumption. The second phenomenon showing a strong correlation with the answers was the declared level of familiarity with the term *bioeconomy.* Declaration of familiarity with the concept of the bioeconomy was positively correlated with acceptance of and openness to bioeconomy products and with expectations upon the legislator regarding

encouraging and obliging producers to adopt sustainable methods of production. Numerous studies confirm the relationship between environmental awareness and purchasing decisions of consumers (Straupaite-Simonavice, Jeyakumar, 2023; Wierzbiński *et al.,* 2021). Even mere familiarisation with the concept seems to have an impact on consumer attitudes.

4.3. What should be the role of the legislator in implementing the principles of bioeconomy?

Large-scale surveys show that most EU consumers expect their governments to actively promote or implement sustainability principles, especially in food systems: 52% in the North-West EU countries and 43% in the South-East EU countries (De Boer, Aiking, 2022). While the study points to the need for more ambitious legislation at EU level (Pollex, 2017), consumers generally prefer less intrusive government interventions, such as information campaigns, eco-labels, and incentives, over direct regulation. Acceptance of more coercive measures is lower (Ammann *et al.,* 2025; Faure *et al.,* 2022). In the context of sustainable energy solutions, although consumers generally did not expect the implementation of stronger regulation in the form of compulsory measures, there are strong indications that their acceptance of such measures increases significantly if they are accompanied by a high level of trust in the government and/or a strong environmental identity. In Poland and Sweden, higher trust in the government was associated with a stronger preference for taxes (Faure *et al.,* 2022). Present research conducted among Polish consumers confirms the phenomenon of expectations towards the legislator. Consumers in the surveyed population have strong expectations for actions promoting the bioeconomy and its products but also imposing this approach to production. With regard to the promotion of organic and sustainable food production, the sum of strongly agree and agree responses was nearly 70%, and almost 50% of respondents supported the legal imposition of food production standards. Regarding industrial goods, nearly 80% of respondents expected stronger promotion, and nearly 50% expected legislative action imposing biobased solutions. Even people who are more sceptical about the use of bioeconomy products expect more information and promotion of its solutions.

5. Conclusions

Majority of consumers in Poland are ready for and expect the introduction of bio-based products. It can be expected, that the openness of consumers will increase with their level of prosperity. Acceptance of all solutions of the bioeconomy is not however uniform across the survey sample. Organic food, as an example of sustainable agricultural production, on the market for many years now, has already found its audience. The bioplastics and bio-based materials are of interest to consumers and the majority of the surveyed population do not have

any prejudices against such materials. The ambivalent attitude to biogas plants is visible and requires further research. As biogas is a potentially important element in the energy mix, it should be promoted in a way which is independent of political discourse. The policy of decarbonisation has become one of the topics of a much broader conflict of worldviews in society and exploited at a political level. Due to the potential of the bioeconomy as an integral part of a decarbonisation strategy and environmental goals, there is a risk of politicisation of its goals. As the study showed, the factors of material status and declared knowledge of the studied concept had the strongest influence on consumer attitudes. While it is not possible to bring about a change in the economic status of the population in a short time period, it is possible to start a public discourse and introduce the term *bioeconomy* to common usage, in a context which is independent of phenomena polarising society. It is thus recommended to familiarise people with the concept and to root it neutrally in the language used by stakeholders. As in the case of the certification of organic food, the certificate and a symbol expressing it must be clear and easy to recognise. It seems especially important for the legislator to take actions to further raise awareness among consumer and producers, and to employ incentives to encourage the latter to implement the principles of cleaner production. There is strong support for the policy of promoting such principles on producers in practice, though this needs to be done carefully, as it could lead to the politicisation of the bioeconomy mentioned above.

The study conducted has its limitation, especially in the context of the composition of the research sample. The sample could not be selected based on quotas due to the lack of consent from potential respondents. The most important limitation may be considered to be the high level of education of the respondents, which does not reflect the structure of education in society. According to data from the Statistical Yearbook of Poland 2024, 24.5% of the population were educated to tertiary level (Mały rocznik statystyczny, 2024 (Concise Statistical Yearbook of Poland, 2024) 2024), and 34.3% were educated to secondary level. In the sample for this study, the values were 44% in both cases. People with a lower level of education were less likely to grant consent to participate in a survey.

Declaration of Generative AI Use: The author have not used any generative AI in the preparation of this work.

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Annex 1

Sample characteristic

Gender	F								M							
	262								238							
Age	18-29 y.o.				30-39 y.o.				40-49 y.o.				50-59 y.o.		Over 60 y.o.	
	75				89				101				73		162	
Place of residence	Village				Town up to 20,000				Town 20,000-100,000				Town 100,000-200,000		Town 200,000-500,000		City over 500,000	
	86				43				133				58		69		111	
Voivodship*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	41	27	27	12	33	44	73	12	28	13	29	59	14	18	47	23
Net income per capita in the household**	Up to 1000 PLN (~235 EUR)				1001-2000 PLN (~470 EUR)				2001-3500 PLN (~820 EUR)		3501-5000 PLN (~1172 EUR)		5001-8000 PLN (~1875 EUR)		Over 8000 PLN (~1875 EUR)	
	0				6				172		138		80		30	
Education	Primary				Vocational				Secondary				Higher			
	7				49				222				222			

* 1) Dolnośląskie, 2) Kujawsko-Pomorskie, 3) Lubelskie, 4) Lubuskie, 5) Łódzkie, 6) Małopolskie, 7) Mazowieckie, 8) Opolskie, 9) Podkarpackie, 10) Podlaskie, 11) Pomorskie, 12) Śląskie, 13) Świętokrzyskie, 14) Warmińsko-Mazurskie, 15) Wielkopolskie, 16) Zachodniopomorskie.

** Conversion from PLN to EUR at exchange rate on: 01/11/2024.

Survey questions

- *Understanding bioeconomy*
  1. **Are you familiar with the concept of the "bioeconomy"?**
     - Yes
     - No
     - I am not sure
  2. **Which of the following terms do you associate with the concept of bioeconomy?** (multiple choice)
     - Biomass
     - Biofuels
     - Bioplastics
     - Biotechnology
     - Circular economy
     - Innovation
     - Forest production
     - Agricultural production
     - Organic agrriculture
     - Biobased goods
     - Organic farming
     - I have no associations with the term bioeconomy
     - Others…

- *Consumers perception of the bioeconomy products*
  3. **I like to buy organic products even though, their price is sometimes higher than conventional products**
     - I strongly agree
     - I agree
     - I am not sure
     - I disagree
     - I strongly disagree
  4. **I would gladly use plastic and materials (e.g. bottles, reusable packaging and other everyday materials and items) made from biological materials instead of conventional plastics and non-renewable materials, even if their price would be slightly higher**
     - I strongly agree
     - I agree
     - I am not sure
     - I disagree
     - I strongly disagree
  5. **Industrial bio-based materials (e.g. bottles, reusable packaging and other everyday materials and items):**
     - Such materials are definitely better quality than those made from non-renewable resources
     - Such materials are rather of better quality than those made from non-renewable resources
     - Such materials are of the same quality as those made from non-renewable resources
     - Such materials are probably of worse quality than those made from non-renewable resources
     - Such materials are definitely of much worse quality than those from non-renewable resources
     - I have no opinion
  6. **Would you have any objections if a biogas plant were to be built near your place of residence?**
     - I strongly agree
     - I agree
     - I am not sure
     - I disagree
     - I strongly disagree

- *Legislators role*
  7. **I believe that the government should more strongly promote and encourage farmers to implement the principles of more environmentally friendly food production**
     - I strongly agree
     - I agree
     - I am not sure
     - I disagree
     - I strongly disagree

8. **I believe that the government should impose on producers, through legal acts, the implementation of principles of more environmentally friendly food production**
   - o I strongly agree
   - o I agree
   - o I am not sure
   - o I disagree
   - o I strongly disagree
9. **I believe that the government should promote and encourage manufacturers to produce biobased materials, goods and energy**
   - o I strongly agree
   - o I agree
   - o I am not sure
   - o I disagree
   - o I strongly disagree
10. **I believe that the government should impose on producers, through legal acts, the production of materials, goods and energy that would be produced from biological resources and/or recovered non-renewable raw materials**
   - o I strongly agree
   - o I agree
   - o I am not sure
   - o I disagree
   - o I strongly disagree

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DIFFUSION OF CERTIFIED MANAGEMENT SYSTEMS IN POLAND IN THE YEARS 2018-2023

Marek SZAFRANIEC

Silesian University of Technology, Faculty of Organization and Management, Department of Production Engineering; marek.szafraniec@polsl.pl, ORCID: 0000-0002-9827-280X

Purpose: The main aim of the paper is to update and extend evidence on the diffusion of ISO-based management system certifications in Poland in 2018-2023, quantifying dynamics (levels, YoY changes) and the current sectoral profile across six widely adopted standards. The achievement of this main objective is preceded by a verification of the chronology of the diffusion of the specific subject matter of the standards over time.
Design/methodology/approach: A quantitative, longitudinal analysis based on secondary data from the 2018–2023 ISO Survey was employed. Certificates were operationalized, and a selection filter was applied to focus on six cross-sector standards (ISO 9001, 14001, 45001, 50001, ISO/IEC 27001, ISO 22301), while highly sector-specific or nascent standards were excluded. Time-series indicators (levels, YOY) and a 2023 sectoral cross-section were computed using the ISO sector taxonomy.
Findings: The obtained results indicate that (1) The certification uptake is definitely sector-concentrated rather than uniform across the economy. (2) The ISO 9001/14001 standards dominate volumes but show stabilization/soft declines after the 2019 pre-pandemic peak. (3) The newer OH&S (ISO 45001) and the energy (ISO 50001) systems grow steadily from a lower base. (4) The certification volume of most standards decreased in the first year of the COVID-19 pandemic. (5) There are sectors with high certification rates for all systems (e.g.: Basic metal & fabricated metal products, Wholesale & retail trade, Electrical and optical equipment), but there are also sectors characteristic of selected standards (e.g.: Transport, storage and communication / Gas supply).
Research limitations/implications: The study is limited by its reliance on aggregated secondary data from the ISO Survey, where data reporting by national accreditation and certification bodies is voluntary.
Practical implications: The results can inform policymakers and accreditation bodies in designing targeted support mechanisms to encourage certification in lagging sectors. For businesses, the findings provide benchmarks and strategic insight into sectoral trends.
Originality/value: This paper offers an updated, Poland-focused, multi-standard, sector-specific analysis of certification diffusion in Poland, filling a gap in the literature by integrating multi-year ISO Survey data with a theoretical perspective. It is particularly relevant to researchers, indicating the need for more detailed, in-depth research, as well as to consultants and decision-makers.
Keywords: Certified management systems, ISO, COVID-19, sectoral analysis, Poland.
Category of the paper: Research paper.

Introduction

Since the ISO introduced the first standard of management systems in 1987, the Quality Management System, organizations around the world have shown a continuously increasing interest in their implementation (Franceschini et al., 2006). Over the years, the number of worldwide certificates for compliance with the ISO 9001 standard has been on the increase (Cabecinhas et al., 2018; Podrecca, Sartor, 2023). However, the publication of new standards was rather slow (cf. Table 1 and Figure 1). Between 1987 and 2002, only three standards in two areas of management appeared: in quality and in environment These standards also attracted considerable interest among organizations (Casadesús et al., 2008). More standards appeared in the following years. There were more detailed, industry-specific standards in the area of quality management, as well as standards in other areas of management. As previously mentioned, the following areas of management were included in the standardization: quality and environmental management first, followed by: social security, food safety, information technology, energy, event sustainability, asset, anti-bribery, occupational health and safety (OH&S) and innovation management. The level of interest in implementing these standards remained high, as evidenced by their degree of diffusion (Lira et al., 2018; Granja et al., 2021). The content and structure of individual standards have also changed over the years. Table 1 lists the chronological list of the ISO key standards for management systems, together with the area to which they apply, the symbol abbreviation, the year of publication of the first version and the current version of the standard. General information is shown graphically in Figure 1.

Table 1.
Core information on the timing and scope of introduced ISO management system standards

Date of the standard introduction	Standard symbol/code and title	
	First edition	Current version
March 1987	ISO 9001:1987 Quality systems — Model for quality assurance in design/development, production, installation and servicing	ISO 9001:2015 Quality management systems – Requirements
September 1996	ISO 14001:1996 Environmental management systems — Specification with guidance for use	ISO 14001:2015 Environmental management systems -- Requirements with guidance for use
December 1996	ISO 13485:1996 – Quality systems — Medical devices — Particular requirements for the application of ISO 9001	ISO 13485:2016 Medical devices — Quality management systems — Requirements for regulatory purposes
September 2003	ISO/TS 29001:2003 Petroleum, petrochemical and natural gas industries — Sector-specific quality management systems — Requirements for product and service supply organizations	ISO 29001:2020 Petroleum, petrochemical and natural gas industries — Sector-specific quality management systems — Requirements for product and service supply organizations
September 2005	ISO 22000:2005 Food safety management systems — Requirements for any organization in the food chain	ISO 22000:2018 Food safety management systems — Requirements for any organization in the food chain

Cont. table 1.

October 2005	ISO/IEC 27001:2005 Information technology — Security techniques — Information security management systems — Requirements	ISO/IEC 27001:2022 Information security, cybersecurity and privacy protection — Information security management systems — Requirements
December 2005	ISO/IEC 20000-1:2005 Information technology — Service management. Part 1: Specification	ISO/IEC 20000-1:2018 Information technology — Service management. Part 1: Service management system requirements
September 2007	ISO 28000:2007 Specification for security management systems for the supply chain	ISO 28000:2022 Security and resilience — Security management systems — Requirements
June 2011	ISO 50001:2011 Energy management systems — Requirements with guidance for use	ISO 50001:2018 Energy management systems — Requirements with guidance for use
May 2012	ISO 22301:2012 Societal security — Business continuity management systems — Requirements	ISO 22301:2019 Security and resilience — Business continuity management systems — Requirements
June 2012	ISO 20121:2012 Event sustainability management systems — Requirements with guidance for use	ISO 20121:2024 Event sustainability management systems — Requirements with guidance for use
October 2012	ISO 39001:2012 Road traffic safety (RTS) management systems — Requirements with guidance for use	ISO 39001:2012 Road traffic safety (RTS) management systems — Requirements with guidance for use
January 2014	ISO 55001:2014 Asset management — Management systems — Requirements	ISO 55001:2024 Asset management — Asset management system — Requirements
September 2015	ISO 18788:2015 Management system for private security operations — Requirements with guidance for use	ISO 18788:2015 Management system for private security operations — Requirements with guidance for use
October 2016	ISO 37001:2016 Anti-bribery management systems — Requirements with guidance for use	ISO 37001:2025 Anti-bribery management systems — Requirements with guidance for use
March 2017	ISO 44001:2017 Collaborative business relationship management systems — Requirements and framework	ISO 44001:2017 Collaborative business relationship management systems — Requirements and framework
March 2018	ISO 45001:2018 Occupational health and safety management systems — Requirements with guidance for use	ISO 45001:2018 Occupational health and safety management systems — Requirements with guidance for use
May 2018	ISO 21001:2018 Educational organizations — Management systems for educational organizations — Requirements with guidance for use	ISO 21001:2025 Educational organizations — Management systems for educational organizations — Requirements with guidance for use
December 2018	ISO 21401:2018 Tourism and related services — Sustainability management system for accommodation establishments — Requirements	ISO 21401:2018 Tourism and related services — Sustainability management system for accommodation establishments — Requirements
July 2019	ISO 56002:2019 Innovation management — Innovation management system — Guidance	ISO 56002:2019 Innovation management — Innovation management system — Guidance
April 2021	ISO 37301:2021 Compliance management systems — Requirements with guidance for use	ISO 37301:2021 Compliance management systems — Requirements with guidance for use
July 2021	ISO 37002:2021 Whistleblowing management systems — Guidelines	ISO 37002:2021 Whistleblowing management systems — Guidelines

Source: Own study.

It can be concluded from Table 1 that the standards themselves were improved over time. A change in the content, or in some requirements, resulted in at least a change in the standard symbol. At that time, there was a certain transition period for organizations to adapt to new requirements without losing the certificate. Sometimes the changes in the content were so significant that the result was a change in the standard title. New areas of management were covered in the first period (1987-2002) only occasionally. In later years this occurred more frequently. Especially the years 2005 and 2012, and the period between 2017 and 2020 marked the appearance of many more standards relating to new management areas. The structure of the content of the standards was also improved. In this respect, they currently use (versions of standards created after 2012) the Unified High-Level Structure and consist of 10 unified chapters: (1) Scope; (2) Normative references; (3) Terms and definitions; (4) Context of the organization; (5) Leadership; (6) Planning; (7) Support; (8) Operation; (9); Performance evaluation; (10) Improvement. Compared to their earlier versions, the standards now take account of the need for the process approach, risk analysis, consideration of the special importance of leadership and of the analysis of the context of the organization. The basic feature of these systems is the obligation to continuously improve the organization in the relevant area.

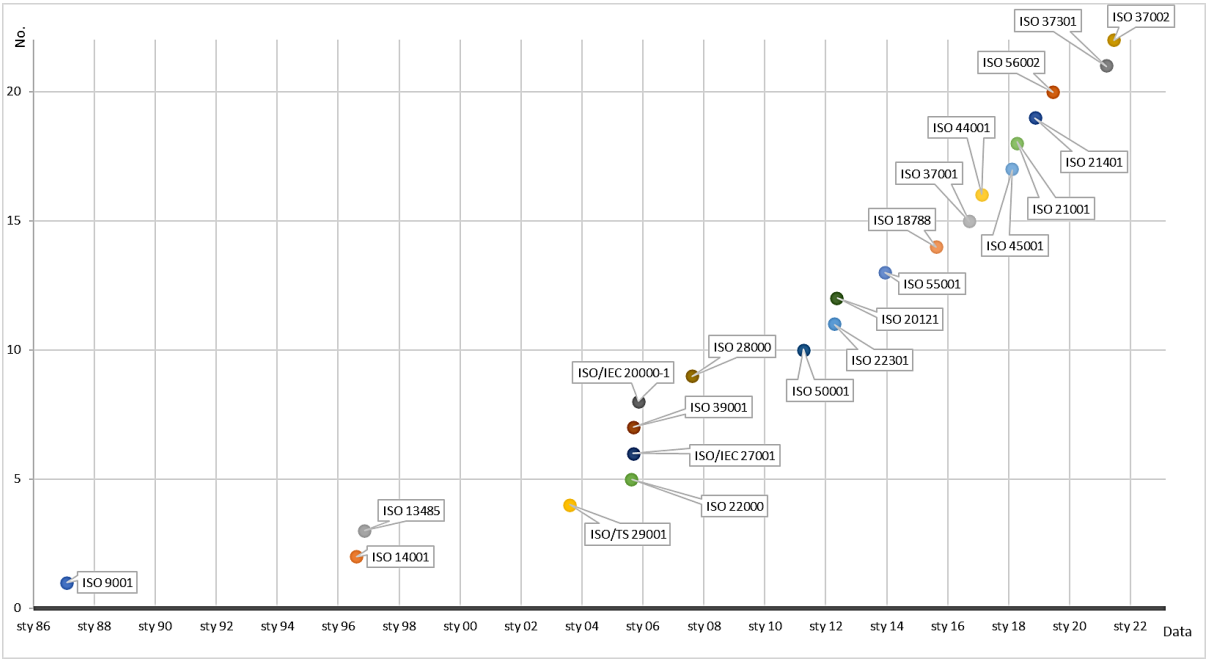


Figure 1. Graphical presentation of the chronology of the implementation of ISO standards in the field of management systems.

Source: Own study.

The adoption of the requirements of management system standards is voluntary for organizations. Nevertheless, they feel motivated to implement them, which manifests itself in the growing interest in the standards worldwide (Liu et al., 2019; Toporowicz et al., 2020; Zubeltzu-Jaka et al., 2024).

The process of the diffusion of management systems based on ISO standards reflects both the development of global standardization initiatives and the changes in socio-economic priorities. Several significant factors have appeared recently that may influence the decision whether an organization will keep or obtain the ISO certification for the compliance of its management systems with the requirements of ISO standards. This primarily concerns the factors affecting the economic system and the existing logistics channels, such as the Covid-19 pandemic, or wars in Ukraine or in the Middle East. The latest versions of the ISO 9001 and 14001 standards were created in 2015. In 2018 the ISO 45001 and the new 50001 standard were created, and the year 2019 marked the publication of the ISO 22301 standard. Therefore, it was decided to take account of the post-2018 data to also consider the impact of these phenomena on the decisions of individual organizations concerning certified management systems.

One indicator of the diffusion of standardization is the number of valid certificates for the compliance of management systems with standards. It is monitored and published annually as part of the ISO Survey. These data present, among others, the number of active certificates divided by country, region and sector of the economy.

Over the years, researchers have examined the diffusion of management system certifications in accordance with ISO standards. These analyses have addressed both global and regional perspectives (Daddi et al., 2015; Lira et al., 2021), as well as the national context of Poland (Ejdys et al., 2012; Kozel et al. 2017; Cierpioł, Wąsikiewicz-Rusnak, 2021). Studies have included both historical data and attempts to forecast future developments in certification trends (Ikram et al., 2019; Basaran, 2021). Updating knowledge in this area serves a dual role: it continues previous research and provides an opportunity to verify earlier findings. Therefore, the main objective of this paper is to update and supplement knowledge on the dynamics of changes in the volume of certification of management systems based on ISO standards in Poland in recent years using the ISO Survey data. In particular, this concerns changes in the number of certificates for compliance with the requirements of standards, and presentation of the current state of the number of implementations in individual industries. Before this main objective is achieved, the chronology of the formation of standards and of the diffusion of their specific subject matter over time is verified.

Methods

The input data used in the research come from the ISO Survey, published annually by the International Organization for Standardization (ISO). These databases are created based on the data reported voluntarily by member organizations – national accreditation and certification bodies.

The ISO Survey has its limitations due to the fact that data reporting is voluntary within the system. The reporting is the responsibility of national accreditation and certification bodies, which can sometimes lead to gaps and inconsistencies in the number of certificates over time. For example, the 2023 edition failed to include data from China, which for years was the world's leader in the number of certificates. This fact significantly affected the values of global rankings (ISO, 2024). As for Poland, not all certification bodies participated in reporting certification data for the ISO 9001 standard in 2022 (there are now 41 such bodies). This leads to unexpected fluctuations in the number of certificates at that time. Despite these limitations, the ISO Survey remains the most important global source of quantitative data on the certification of management systems. It is a valuable source of data, which is confirmed by their wide use in papers that appear in important world journals (To, Lee, 2014; Neves et al., 2018; Lira et al., 2021).

In the first stage of the research, all current standards for management systems published by the ISO were analysed. The theoretical part of the paper ('Introduction') presents the process of the diffusion of the standards over time, considering the dates of their introduction, the areas they covered and the introductory and current versions.

For the purposes of the empirical part, a selection approach was applied to the standards, taking account of the specificity of the ISO Survey data and the cross-sectional nature of the planned industry-specific analyses. Therefore, in the next stages the following were excluded:

1. Standards not covered by the ISO Survey reporting system.
2. Industry standards – dedicated exclusively to selected sectors (e.g. the ISO 13485 standard for medical devices, the ISO 22000 standard for food safety, etc.).
3. New standards – not yet observed for a sufficient number of years.
4. Marginal standards – for which the number of certificates is small, which could distort conclusions due to data incompleteness and differences in reporting.

Finally, the following standards were selected for the statistical analysis:

- ISO 9001 – quality management systems,
- ISO 14001 – environmental management systems,
- ISO 45001 – occupational health and safety management systems,
- ISO 50001 – energy management systems,
- ISO/IEC 27001 – information security management systems,
- ISO 22301 – business continuity management systems.

The time span of the analyses was selected as 2018-2023. This choice was justified by the significant changes in the content of key standards in 2015 (this concerned standards ISO 9001 and ISO 14001) and the introduction of a transition period for organizations to adapt to them, which undoubtedly contributed to fluctuations in certification volumes (Camango et al., 2023). The ISO 45001 standard was introduced, replacing the existing OHSAS 18001 standard. This finding highlights the need for further research into the dynamics of certification in this critical area of management. The year 2018 was therefore considered a logical starting point for conducting trend analyses.

For selected standards, analyses of the trends in the change in the number of certificates for organizations and sites (for the years 2018-2023) and sectoral diffusion for organizations (for the year 2023) were carried out. A certificate refers to the official document granted by a certification body once an organization has demonstrated compliance with the standard requirements. A site refers to a fixed physical location where the organization conducts its activities or delivers services. The trends were calculated as the number of certificates in individual years and their percentage difference year-on-year. Sectoral diffusion was presented as the number of certificates in individual industries for compliance with each of the standards selected for the analysis. In addition, the industries with the highest and the lowest numbers of those certificates were determined.

Results

The analysis of the data concerning Poland and taken from the ISO Survey reports from the years 2018-2023 points to a varied dynamics of the number of certificates of the management systems tested in the certification areas. Figure 2 and Table 2 show that, depending on the standard under consideration, both increases and decreases in the number of certificates could be observed in the studied period.

In particular, in terms of scale values and general trends:

- The ISO 9001 standard remains by far the most common management system in Poland, but its number of certificates recently showed fluctuations at a level below 11500. In 2023, the number of certificates of organizations totalled 11276, with a maximum in the analysed period of 11460 in 2019 – the year before the outbreak of the COVID-19 pandemic. The number of certifications for the most widely adopted standards, both globally and in Poland, had already fluctuated in earlier years, due in part to the need to adapt to evolving requirements (Ejdys et al., 2012).

- The ISO 14001 is the second most widely certified standard. In 2023 the number of certificates totalled 3213, with a maximum of 3766 in 2019. As in the case of the ISO 9001 standard, the maximum value was achieved in the year before the pandemic.
- The ISO 45001 is a standard whose number of certificates for compliance with its requirements is growing rapidly. The first version of the standard was created in 2018, but already at the end of the analysed period, in 2023, there were 2064 certificates, with a continuous and strong rise from one year to another. The highest rise in the number of certificates was recorded in 2020. It totalled 884, which was a almost three and a half times increase compared to the previous year.
- The ISO/IEC 27001 is the standard with the fourth highest number of certificates. Although the number fluctuated over the analysed time, it generally showed a slightly rising trend. In 2023, 846 certificates were reported, with a maximum in 2021 totalling 876.
- The ISO 50001 standard ranks fifth in this respect. It recorded an increase in each year of the period under consideration. The highest numbers of increase are for years 2021 and 2020, which contrasts with the trends in the number of certificates for the most important standards, where drops were observed during the pandemic. This may be due to the fact that a lot fewer certificates were granted and that the country's economy was not sufficiently saturated with them. In 2023, the number of certificates totalled 266. Effective energy management is critical to the energy security of Poland and the European Union (Janik et al., 2021).
- The ISO 22301 standard recorded the lowest number of certificates for the standards under analysis but shows a slow but steady increase in certification.

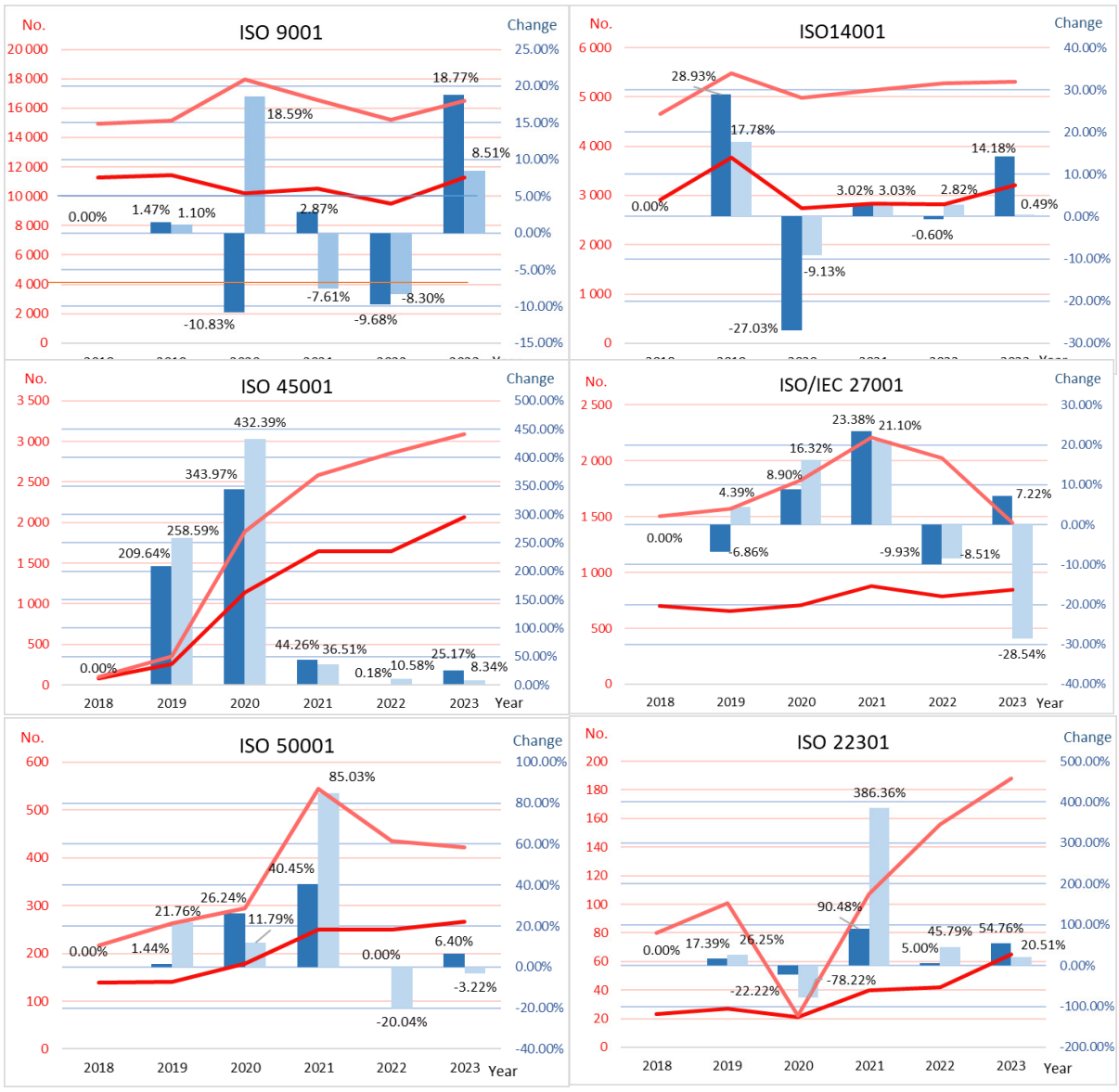


Figure 2. Number of certificates of organizations and sites and changes thereof in 2018-2023 according to the ISO Survey.

Source: Own study based on the ISO Survey 2018-2023.

The results of the cross-sector analysis are presented in Table 2.

Table 2.
Number of certificates for compliance with ISO standards of management systems in 2023 in Poland by industry

Sector	ISO 9001	ISO 14001	ISO 45001	ISO 27001	ISO 50001	ISO 22301
Agriculture, Fishing and Forestry	5	3	2	0	6	0
Mining and quarrying	36	30	27	2	2	0
Food products, beverage and tobacco	119	71	7	0	28	0
Textiles and textile products	92	27	8	0	0	0
Leather and leather products	3	2	1	0	0	0
Manufacture of wood and wood products	77	18	7	0	12	0
Pulp, paper and paper products	158	61	13	0	5	0
Publishing companies	34	12	4	0	0	0
Printing companies	136	36	5	2	0	1
Manufacture of coke & refined petroleum products	18	10	6	0	2	0
Nuclear fuel	0	0	0	0	0	0
Chemicals, chemical products & fibres	238	90	40	1	15	0
Pharmaceuticals	7	6	2	0	1	0
Rubber and plastic products	717	245	77	4	21	0
Non-metallic mineral products	95	102	22	1	9	0
Concrete, cement, lime, plaster etc.	75	37	14	0	1	0
Basic metal & fabricated metal products	1798	521	295	3	40	1
Machinery and equipment	736	239	188	8	6	0
Electrical and optical equipment	748	231	136	18	15	0
Shipbuilding	39	10	6	0	0	0
Aerospace	16	1	2	0	1	0
Other transport equipment	244	87	44	1	12	0
Manufacturing not elsewhere classified	101	41	14	0	0	0
Recycling	84	84	26	4	9	0
Electricity supply	33	40	25	3	11	7
Gas supply	53	8	31	1	20	24
Water supply	54	122	82	1	5	2
Construction	542	214	260	5	4	0
Wholesale & retail trade, repairs of motor vehicles, motorcycles & personal & household goods	1050	245	96	22	16	0
Hotels and restaurants	31	12	5	0	0	0
Transport, storage and communication	504	174	83	20	5	96
Financial intermediation, real estate, renting	84	43	9	13	8	0
Information technology	178	35	15	178	3	9
Engineering services	427	150	136	19	6	0
Other Services	524	147	77	26	3	8
Public administration	73	6	4	10	0	5
Education	366	16	19	9	2	3
Health and social work	1031	88	36	98	0	8
Other social services	106	110	120	140	2	1

Note: For given standards, the highest and the lowest 10 values are marked in **red** and **blue**, respectively. The table does not contain certifications for which the industry was not defined/was unknown.

Source: Own study based on the ISO Survey 2018-2023.

As regards the cross-sectoral analysis, in particular it was observed that (cf. Table 2):

- the sectors characterized by the highest number of certificates in the analysed areas of management are as follows: Wholesale & retail trade, repairs of motor vehicles, motorcycles & personal & household goods; Electrical and optical equipment (both rank in the top 10 in relation to 5 standards); Basic metal & fabricated metal products; Electrical and optical equipment; Rubber and plastic products; Transport, storage and communication; Engineering services; Other Services (included in the top 10 in relation to 4 standards).
- The highest number of certificates in individual areas of standards were recorded by the following sectors (three industries with the highest number of certificates):
  - ISO 9001: Basic metal & fabricated metal products; Wholesale & retail trade, repairs of motor vehicles, motorcycles & personal & household goods; Health and social work.
  - ISO 14001: Basic metal & fabricated metal products; Wholesale & retail trade, repairs of motor vehicles, motorcycles & personal & household goods; Rubber and plastic products.
  - ISO 45001: Basic metal & fabricated metal products; Construction; Machinery and equipment.
  - ISO 27001: Information technology; Other social services; Health and social work.
  - ISO 50001: Basic metal & fabricated metal products; Food products, beverage and tobacco; Rubber and plastic products.
  - ISO 22301: Transport, storage and communication; Gas supply; Information technology.

Summary and conclusions

As shown by the research results, the standardization of management systems, which began with the development of the first quality management standard in 1987, covers wider and wider areas of management. The standards currently apply to areas such as quality, environmental, social security, food safety, information technology, energy, event sustainability, asset, anti-bribery, occupational health and safety (OH&S) and innovation management.

The conducted analysis made it possible to capture the dynamics and structure of the diffusion of certified management systems in Poland in the years 2018-2023. The results confirm that the process is sector-specific. Management systems based on the ISO standards are not implemented evenly across the economy. Diffusion is clearly sectoral in nature – industrial sectors such as metal production, electrical and optical equipment, as well as trade and logistics, dominate.

The use of the sectoral approach made it possible to identify certification leaders and outsiders. This can be a starting point for the development of public policies and strategies supporting the implementation of management systems in less active sectors.

The obtained results confirmed the growing interest in certification of management systems by organizations. However, the dynamics of changes in the case of standards with a long history, such as ISO 9001 or ISO 14001, is much lower than of those created later, such as ISO 50001 or ISO 45001. This is undoubtedly related to the level of saturation with certificates.

Among those analysed, the ISO 9001 standard is the most widespread, but the dynamics of its growth in certification has decreased in recent years. The ISO 14001 standard shows a similar trend, but at lower numbers of certificates. The "younger" standards (with a shorter history), such as ISO 45001 and ISO 50001, are characterized by a steady increase in certification, which may indicate the growing importance of OSH and energy efficiency issues in the operational management of organizations, but this process is also undoubtedly related to the effect of the novelty of the standards themselves.

The year 2020, i.e. the beginning of the COVID-19 pandemic, coincides with temporary drops in the number of certificates for almost all standards. Only the newly introduced standards achieve a rise then. The effect of their novelty may overcome the problems with maintaining and obtaining certificates by organizations during this period. However, this phenomenon requires further and more detailed research.

There are some imperfections in the ISO Survey data collection system due to the voluntary nature of reporting and the risk of gaps in the reports. Nevertheless, these data remain the most important source of information on macro trends and diffusion of industry-specific management systems based on the ISO standards.

This paper also points to the need for more detailed, in-depth research into the causes of the existing fluctuations in the number of certificates for the most recognized management standards based on the ISO requirements. Further research should focus on identifying the predictors of interest in certification of management systems, e.g. economic parameters.

Acknowledgements

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CROWDFUNDING OPPORTUNITIES AS AN ALTERNATIVE FUNDING SOURCE IN THE MUHAMMADIYAH INDONESIA MERCHANT NETWORK

Sentot Imam WAHJONO[1*], Anna MARINA[2], Tri KURNIAWATI[3], Soo-Fen FAM[4]

[1] Universitas Muhammadiyah Surabaya, Indonesia; sentot.imamw@fe.um-surabaya.ac.id, ORCID: 0000-0001-7464-6283
[2] Universitas Muhammadiyah Surabaya, Indonesia; annamarina@um-surabaya.ac.id, ORCID: 0000-0002-3640-5179
[3] Universitas Muhammadiyah Surabaya, Indonesia; trikurniawati@um-surabaya.ac.id, ORCID: 0000-0001-6648-5790
[4] Universiti Teknikal Malaysia Melaka, Malaysia; famsoofen@utem.edu.my, ORCID: 0000-0001-9439-6074
* Correspondence author

Purpose: This study aims to investigated the potential of crowdfunding as an alternative funding mechanism for businesses within the Muhammadiyah Merchant Network (JSM) in Indonesia.
Design/methodology/approach: This study uses a quantitative approach with a survey method and data collection through questionnaires distributed to 325 business operators acquainted with crowdfunding platforms in Indonesia.
The data analysis technique uses multiple regression to test the influence and significance between variables.
Findings: The results show that fundraising, product testing, and established relationship are a positive and significant influence on the success of the crowdfunding platform.
Research limitations/implications: This research needs to be followed up with a qualitative approach to see in more detail how the variables studied or perhaps other variables can influence the success of crowdfunding as a source of business funding.
Social implications: This research has an impact on the financial economic literacy of the community, especially for business people, regarding broader funding sources, not just banking. Therefore, regulations are needed to protect the community and investors or fund providers in a balanced manner.
Originality/value: This article offers an original contribution that combines theory and practical insights emphasizing crowdfunding's relevance as a financial tool in the fast-developing economies of Southeast Asia.
Keywords: crowdfunding, fundraising, product testing, established relationship, Muhammadiyah merchant network.
Category of the paper: Research paper.

1. Introduction

Access to finance is a pivotal determinant of entrepreneurial success (Liu et al., 2015). However, traditional financial institutions have become increasingly hesitant to fund entrepreneurial ventures, particularly after the global economic crisis (Tanrisever, Wismans, 2016). This reluctance, primarily driven by the high risks associated with market volatility and technological innovations, has left technology-based projects and startups with limited funding options. Crowdfunding has consequently emerged as a transformative funding approach, offering an inclusive platform for financial support.

The purpose of this article is to assess the suitability of crowdfunding as an alternative source of business financing, specifically for the specific needs of businesses within a faith-based organization, specifically Muhammadiyah in Indonesia. This analysis focuses on key barriers to financing innovation and explores how crowdfunding mechanisms can help address them. The article also discusses the nature of crowdfunding, its main models, and the procedures involved in fundraising.

As defined by Liu et al. (2015), crowdfunding is an alternative financing strategy that substitutes conventional financial mechanisms. Fundamentally, it involves an open call to individuals and organizations to support projects or ventures financially, often through small contributions. The ownership of these projects remains with the initiators, while the financial backing stems from a collective of supporters (Wahjono et al., 2021). Notably, advancements in digital technologies have enhanced the prominence of crowdfunding, particularly Web 5.0 innovations (Wahjono et al., 2020). Beyond fundraising, crowdfunding serves as a means of garnering additional insights and testing market viability for new ideas (Wahjono et al., 2018).

2. Literature Review

In developing nations, economic activities are predominantly driven by Micro, Small, and Medium Enterprises (MSMEs), most of which operate within the trade sector (Wahjono et al., 2015). These enterprises heavily rely on financial support from banks. However, almost half of MSME loan applications are denied, in contrast to multinational corporations' mere 7% rejection rate. Similarly, nearly all loan requests from startups are rejected (Bouncken et al., 2019). This disparity compels financial experts to explore alternative, equitable funding sources outside the banking system, enabling entrepreneurs to access capital from diverse community resources (Wahjono et al., 2015).

One such alternative is crowdfunding, which provides a platform for individuals or groups to obtain financial backing for projects or businesses from a collective audience (Tanrisever, Wismans, 2016). Crowdfunding is typically categorized into three types: donations, loans, and investments (Fam et al., 2022). In donation-based crowdfunding, contributors do not expect any financial returns as their contributions are made with prior knowledge of the cause and without the anticipation of repayment (Care et al., 2018). Conversely, loan-based crowdfunding involves funders expecting profit and repayment within the project's lifespan. In the investment-based model, contributors provide funds with the expectation of acquiring ownership stakes, evidenced by shares in the venture (Walthoff et al., 2018).

Crowdfunding serves as a mediator, bridging individuals or entities with surplus financial resources to those requiring funding (Borello, Pichler, 2021). The process operates under the framework of registered institutions, which oversee the funding mechanisms (Kshetri, 2018). This platform is open to anyone, including donors or investors with excess funds, and the contributions made are directed through the registered institutions managing the crowdfunding process before being allocated to the intended businesses or projects (Jenkins et al., 2014). Importantly, crowdfunding platforms must be internet-based, ensuring accessibility to users regardless of location or time (Mahamud et al., 2021).

Crowdfunding platform organizers must operate as registered institutions and comply with the financial regulations of their respective countries (Moritz, Block, 2016). The process involves aggregating public funds, which necessitates safeguards to protect the contributors and ensure that crowdfunding platforms adhere to financial security regulations and risk management (Sleuwaegen, Jonas, 2022). While some nations have established legal frameworks to regulate crowdfunding activities, others lack such regulatory measures (Zvilichovsky et al., 2015). In developing countries, crowdfunding platforms are increasingly utilized to support projects and initiatives led by MSMEs and startups (Neville et al., 2020). This paper analyzed the potential of crowdfunding as an alternative financing mechanism for MSMEs and startups.

The global adoption of crowdfunding continues to expand rapidly. In 2018, the total funds raised from investors amounted to $16.2 billion. In the United Kingdom (UK), the crowdfunding market, as highlighted by Nesta (Pakkana et al., 2020), was projected to reach £1.74 billion. Between 2012 and 2020, the sector experienced an average annual growth rate of 150% and is anticipated to grow by 161% between 2016 and 2022. By the end of 2020, the alternative financial market in the UK was expected to contribute over £1 billion in growth and working capital to approximately 7180 MSMEs, representing 2.4% of total business bank loans. Notably, 70% of MSMEs and startups utilizing peer-to-peer (P2P) business loans reported an impressive 63% increase in revenue (Lagazio & Francesca, 2018). As an alternative funding mechanism, crowdfunding has proven instrumental in providing substantial financial support to MSMEs, startups, and socially impactful projects.

According to Ahmad, et al. (2023), crowdfunding can be classified into three primary types: donation-based, loan-based, and equity-based. Donation-based crowdfunding focuses on raising funds for humanitarian or altruistic projects, often without offering financial returns or rewards. These platforms frequently host campaigns aimed at charitable giving, including zakat and waqf contributions.

The crowdfunding process begins with project initiators submitting detailed proposals that outline their objectives, motivations, timelines, and required budgets. These proposals are made available on online crowdfunding platforms, allowing potential funders to review and assess their alignment with the projects' objectives. If funders decide to participate, they complete a form expressing their interest and transfer their contributions to accounts managed by the platform (Massolution, 2019). Once the fundraising goal is achieved, the platform facilitates an agreement between the project initiator and the platform operator, which includes transaction fees, before transferring the funds to execute the project (Walthoff et al., 2018).

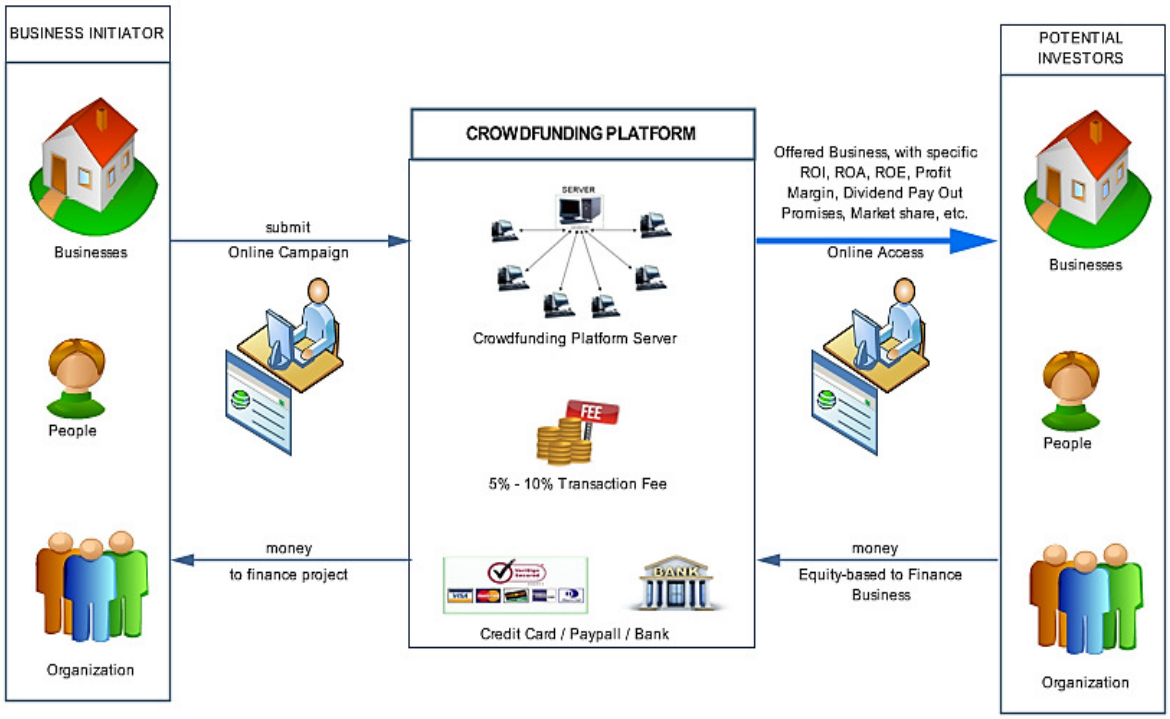


Figure 1. Equity-based crowdfunding mechanism.

Source: Wahjono et al., 2021.

The third crowdfunding category is equity-based crowdfunding, which involves individuals investing in exchange for ownership stakes in MSMEs or startup businesses. In this model, financial contributions are converted into shares of the company. Similar to other equity instruments, the value of these shares fluctuates based on the company's performance—rising as the company's value increases and declining when it decreases (Liu, Liu, 2020). This form of crowdfunding caters to investors seeking tangible ownership as evidence of their investment, represented by company shares (Marina et al., 2019). As shareholders, investors anticipate gaining some control over the business while also benefiting from annual dividends derived

from the company's profits (Dresner, 2020). Figure 1 illustrates the equity-based crowdfunding process.

Based on the research context, this study tested the following hypotheses:

H1: Fundraising positively and significantly impacts the performance of crowdfunding as an alternative funding source.

H2: Product testing positively and significantly impacts the performance of crowdfunding as an alternative funding source.

H3: Relationship building positively and significantly impacts the performance of crowdfunding as an alternative funding source.

As a conclusion to this literature review, the performance of crowdfunding as an alternative source of business funding depends on the ability to carry out fundraising, product testing, and relationship building.

3. Methods

This research uses a descriptive quantitative research design with a survey approach (Yakin et al., 2023). This design was chosen because this research aims to explore the influence of existing variables, namely fundraising, product testing, and relationship building with impact the performance of crowdfunding as an alternative funding source.

This study adopted a quantitative research design. An online survey was conducted using Google Forms to collect data, which served as the primary tool for gathering insights from initiators of equity-based and loan-based crowdfunding campaigns. The use of Google Forms was deemed suitable due to the online nature of crowdfunding platforms, which involve participants from diverse locations. Additionally, this method streamlined the process of validating questionnaire responses. The survey was distributed via the Crowdfunding Indonesia group over four months, from June to September 2024. A non-probabilistic sampling method was employed, where respondents were intentionally selected, and a snowball sampling technique was applied. This approach was used because project initiators often connect with others who have prior crowdfunding experience. The respondents comprised business operators affiliated with JSM in various major cities across Indonesia. Information about eligible participants was obtained through the Secretariat of the Muhammadiyah Central Leadership for the Business, Economic, and Tourism Council (MEBP) in Jakarta.

Population and Sample

Determining the exact population size was challenging due to the broad scope of individuals involved. Consequently, the study focused on project initiators who are members of a Facebook group associated with JSM. Using Krejcie's table, a sample size of 325 was determined. Of the 805 questionnaires distributed to business operators and crowdfunding initiators, 405 were returned. After verifying the responses, only 325 complete and valid questionnaires were included in the analysis. The researchers encountered several obstacles during data collection, including the lack of direct interaction with respondents. However, assistance from MEBP administrators in various cities and provinces helped mitigate some of these challenges (YingYing et al., 2019).

Data Collection Technique

Data were collected through a survey using a questionnaire distributed online. The research instrument used was a questionnaire consisting of statements related to each variable studied. This questionnaire was sent via the WhatsApp platform with a Google Form link that could be accessed by respondents.

The questionnaire instruments used to measure the variables in this study are as follows:

1. Fundraising: These dimensions are measured using statements developed by (Salwa, 2021).
2. Product Testing: This variable was measured using three statements developed by (Prayogo, 2018).
3. Establish Relationship: This variable is measured using ten statements developed by (Azmi, 2020).
4. Crowdfunding Performance: This variable is measured by four statement items developed by (Wahjono, 2021).

Each statement on the questionnaire was measured using a 4-point Likert scale, consisting of:

1 = Strongly Disagree.

2 = Disagree.

3 = Agree.

4 = Strongly Agree.

Respondents were asked to rate the statements based on their experiences and views on social media use and workplace performance.

Research Instruments

This research instrument is a questionnaire containing statements to measure the variables under study. Each item in the questionnaire relates to a specific dimension of the variable being measured, namely fundraising, product testing, and relationship building, and crwodfunding performance. The Likert scale is used to measure the respondent's level of agreement or disagreement with each statement in the questionnaire. This instrument has been tested for validity and reliability to ensure that the data collected can be trusted and provide valid results. Instrument validity was tested using factor analysis, while reliability was tested using Cronbach's alpha (Sekaran, Bougie, 2016).

Data Analysis Technique

The collected data will be analyzed using descriptive and inferential statistical analysis techniques. For descriptive analysis, data will be presented in the form of frequencies and percentages to describe the characteristics of respondents and the distribution of answers to each statement item. Furthermore, inferential analysis will be used to test the hypotheses that have been formulated. Linear regression test and moderation analysis will be used to examine the effect of fundraising, product testing, and relationship building on crowdfunding performance (Tojiri et al., 2023). In addition, reliability and validity tests will be conducted to ensure the consistency and accuracy of the measurement tools used in this study. Data analysis is conducted using statistical software SPSS to ensure the accuracy of the analysis results.

4. Results and Discussion

Respondent Characteristics

Table 1 shows the distribution of respondents based on the demographic characteristics relevant in this study, including gender, age, citizenship, and Length of membership in JSM (years).

Table 1.
Characteristics of Respondents

Characteristics	Frequency (n = 325)	Percentage (%)
Gender		
Male	254	78.2
Female	71	21.8
Age		
15-20 years old	17	5.2
21-30 years old	83	25.5

Cont. table 1.

31-40 years old	92	28.3
41-50 years old	88	27.1
51-60 years old	45	13.8
Citizenship		
Jakarta	114	35.1
Bandung	42	12.9
Yogyakarta	46	14.2
Surakarta	34	10.5
Semarang	22	6.8
Malang	15	4.6
Surabaya	52	16.0
Length of membership in JSM (years)		
1	155	47.7
2	82	25.2
3	63	19.4
4	23	7.1
5	2	0.6

Table 1 illustrates the distribution of respondents' characteristics, which mostly consisted of males (72.2%) reflecting the dominance of men in the business sphere within the Muhammadiyah organization. This suggests that business activities in Muhammadiyah are primarily conducted by men, likely due to their greater flexibility, capacity to engage in external activities, and ability to interact with others more freely. most respondents (69.2%) belonged to the productive age group, with 28.3% aged 31-40 years old, 27.1% aged 41-50 years old, and 13.8% aged 51-60 years old. This underscores the predominance of individuals within the productive age range in the Muhammadiyah business environment. The remaining respondents (30.7%) were aged 21-30 years old (25.5%) and 15-20 years old (5.2%).

These findings suggest that the respondents represent an economically active demographic capable of driving community economic development. They form the core participants in JSM, engaging in business and other economic activities, including crowdfunding. and the age group of 36-45 years (39%). Significant proportion of respondents (35.1%) were based in Jakarta, while others operated their businesses in other major cities on Java, Indonesia's most economically active island. Other key locations include Surabaya (16.0%), Yogyakarta (14.2%), and Bandung (12.9%), which are recognized for their medium to high economic activity. As provincial capitals, Surabaya and Bandung are industrial hubs with vibrant populations and significant financial activity. most respondents (92.3%) have been members of JSM for up to three years, with 47.7% joining within the past year.

Many resident in Jakarta, while others operate in prominent cities on Java with high economic activity, such as Surabaya (16.0%), Yogyakarta (14.2%), and Bandung (12.9%). Surabaya and Bandung are industrial cities with dynamic populations and substantial financial turnover in addition to being provincial capitals. Nearly half of the respondents (48.6%) were self-employed, followed by those employed in the private sector (27.1%). This indicates that most Muhammadiyah business members (75.7%) are engaged in entrepreneurial activities, mainly within the informal sector and outside government employment. Notably, some

respondents were students, suggesting that some had initiated business ventures early, even before completing their higher education.

Hypothesis Test Result

After the data is processed, it produces respondent characteristics as in table 1 and is then entered into a quantitative data processing application (SPSS) to determine the regression between the independent and dependent variables until the coefficient and significance figures are obtained as shown in table 2, then the coefficient figures can be used to answer the hypothesis.

Table 2.
Coefficients & Significancy

Coefficients[a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.180	.170		12.852	.000
	Fundraising	.130	.041	.178	3.137	.002
	Product Test	.177	.045	.226	3.943	.000
	Est Relationship	.128	.032	.196	4.029	.000
[a]Dependent variable: Success of crowdfunding						

Crowdfunding can be one of the funding source options for business people and is especially beneficial for beginners or start-up business people. Although crowdfunding is not yet widespread in Indonesia, crowdfunding platform owners are trying to use various methods to increase public awareness, including through lectures, socialization, business training, and the use of social media to transfer crowdfunding knowledge to the public. To protect the rights of the community and project initiators, the Indonesian government needs to formulate regulations or rules to minimize the risk of fraud and project failure. The implications of this study indicate that crowdfunding not only provides financial benefits but also non-financial benefits. This is especially useful for startup entrepreneurs who want to effectively overcome their financial issues and expand their distribution networks. The level of trust in individuals intending to start their businesses will also increase. This is important because as more startups emerge, job vacancies will increase, leading to better economic scales in the country.

Crowdfunding is highly recommended to be practiced within JSM, considering Muhammadiyah as a community organization aims to develop its contributions to the nation and Indonesia not only in the education, health, and religious social sectors but also in the economic sector. It is an appropriate choice given its inclusive nature.

In addition, there are several recommendations to provide solutions to the limitations of this study and to increase the benefits of similar research in the future. First, extending the timeframe for conducting future research is recommended. More survey forms can be distributed with more time, and more data from a larger target respondent pool can be obtained. Researchers also have time to investigate and contact more Asian crowdfunding platform

owners, allowing more countries' respondents to participate in the survey to ensure the accuracy of the results. The second recommendation, future research should use different and larger population and sample sizes to improve the accuracy of the results and the efficiency of the independent and dependent variables. In addition, a more in-depth analysis can be explored in future research. Also, future research can focus on the size of the creator's social network, by examining how the creator's expertise, the types of projects they launch, and the level of funding can affect the motivation to participate in other business communities in both religious and non-religious business communities.

There are several limitations in this study. The first limitation is time constraints, as there were only about six months to conduct this research project, with the most time-consuming parts being the questionnaire distribution period and data collection. Therefore, this study could not cover all parts of Indonesia. The second limitation is the sample size of respondents. Because the researchers posted the questionnaires directly to the crowdfunding group, it can be assumed that 805 questionnaires were distributed. However, only 505 sets were returned. After filtering eligible respondents, only 325 participated in this study. Due to time constraints, conducting a larger sample size was impossible.

Conflict of Interest

The authors declared there is no conflict of interest.

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RESEARCH ON THE INTENTIONS OF STARTING AN E-BUSINESS IN STUDENT COMMUNITY

Janusz WIELKI[1*], Inessa SYTNIK[2], Artem STOPOCHKIN[2]

[1] Department of Enterprise Management, Faculty of Economics and Management, Opole University of Technology; j.wielki@po.edu.pl, ORCID: 0000-0001-8973-768X
[2] Department of Enterprise Management, Faculty of Economics and Management, Opole University of Technology; i.sytnik@po.edu.pl, ORCID: 0000-0002-7350-9639
[3] Department of Enterprise Management, Faculty of Economics and Management, Opole University of Technology; a.stopochkin@po.edu.pl, ORCID: 0000-0003-2466-3725
* Correspondence author

Purpose: The conducted research dedicated to distinguishing the intentions of starting one's own e-business in the contemporary student environment focuses on the search for correlations between the actual degree of use of Internet technologies in the educational process and daily life, the level of students' acceptance of new technological solutions, and the perceived value from running one's own e-business.
Design/methodology/approach: The study presented here is qualitative in nature. Data was collected on the basis of a voluntary survey of students who studied at Polish universities in the 2023/2024 and the 2024/2025 academic year.
Findings: The study presented here is qualitative in nature. Data was collected on the basis of a voluntary survey of students who studied at Polish universities in the 2023/2024 and the 2024/2025 academic year. The conducted research led to conclusions: 1) the modern student has a high level of technological skills and makes high use of Internet technologies in the educational process and daily life; 2) the increase in the degree of use of Internet technologies contributes to the technological skills and competencies of the modern student, which results in a high level of acceptance of new technological solutions in the student community; 3) the modern student has good intentions with regard to starting their own business for the reason that they perceive great benefits and values from e-business.; 4) the increase in the degree of use of Internet technologies increases the perceived value from own e-business and the high level of acceptance of new technological solutions positively affects the perceived values from starting own e-business.
Originality/value: This leads to the conclusion that establishing one's own e-business is the basis for modern students to validate and update a new technological system. This element is intended to serve as a link between theory and practice, and is also a foundation for the development of the higher education system.
Keywords: e-business; modern student; acceptance of new technological solutions; intention; start own e-business.
Category of the paper: Research paper.

1. Introduction

Modern life is characterized by a sustainable approach to planning and organizing all socio-economic processes, namely the practical implementation of the Concept of Sustainable Development. This concept and the course of its implementation are presented in detail in Agenda 2030 (United Nations, 2015) and concerns the progressive economic transformation on a global scale. The foundation of this transformation is the digital transformation, which has already permanently entered our lives and continues to shape it technologically, bringing cardinal changes to the existing processes of communicating (Colombo et al., 2017; Morrar et al., 2017; Lee et al., 2018; Diaz et al., 2012), consuming (Jung, 2017; Fernandes et al., 2024), studying (Elayyan, 2021), looking for work and carrying (Arntz et al., 2016; Autor, Dorn, 2013; Dries, Verbruggen, 2012) out other socio-economic activities (More, Soumaya, 2019; Farah et al., 2022).

The world of the digital economy is characterized by both the emergence of new challenges and the formation of new opportunities. The shaping of new opportunities in the digital world is closely linked to the acceleration of business processes (Chou, 2018; Mahlangu, Leke, 2024; Munsamy, Telukdarie, 2022; Soh, Connolly, 2020), the simplification of access to diverse tools necessary for economic and daily life, and the delegation of a significant range of activities to devices operating on the basis of artificial intelligence. Such a technological transformation greatly facilitates the process of running a sustainable business, that is, a business that cares not only about current profits, but also about people, the environment and future generations (Baroni, 2024).

Many scientific studies indicate that the digitization of the economy and social life has greatly accelerated information processing and opened up new opportunities for the use of Internet technologies in all areas of human life. As a result of the widespread emergence of Internet technologies, artificial intelligence, big data and other digital tools, business structures have gained new opportunities in the organization of production/service processes and new prospects for development (Benjamin, 2020; Whalley et al., 2021; Hargreaves et al., 2022; Liu et al., 2022). The advancing digitization opens up new opportunities for personal development, especially for young people just entering the path of life. Thanks to Internet tools and artificial intelligence young people are in a better position to organize their lives, analyze their needs and opportunities, and on this basis manage their personal development in a way that meets their own and society's needs (Pan et al., 2016; Miranda et al., 2015; Hiremath et al., 2015). All this contributes not only to improving the daily functioning of business structures and individual people, but also affects the implementation of a long-term strategy for sustainable development of the whole world (Wortmann, Flüchter, 2015; Rowe, Fudge, 2003).

The formation of today's digital economy directed towards sustainability is strongly based on electronic business. It is worth noting that since the end of the last century e-business has firmly entered various areas of economic life, and in the post-COVID-19 years it has already become an indispensable part of society's daily life. Internet technologies are opening up new horizons for the formation of innovative business strategies, and e-business is becoming a launching pad for many young people capable of both creative thinking and proactive action. It is worth adding that entering the e-business zone strongly involves risks and multiple challenges. This is primarily about issues related to cyber security in all its aspects (Hatzivasilis et al., 2020; Maalem et al., 2020; Śliwiński, Piesik, 2021).

The study conducted investigates the intentions of starting one's own e-business in the student community. The study is based on the technology-personal-environment (TPE) paradigm (Jiang et al., 2010): technology - Internet technologies, as technologies used to conduct e-business; person - as a set of personality (behavioral) variables affecting the process of acceptance of new technological solutions and perceived values from one's own e-business; environment - as a set of implicit social rules towards the use of Internet technologies, which can be both imposed and sustained by the attitudes and behaviors of individuals.

2. Theoretical Underpinning and Literature Review

The theoretical underpinning of the research conducted is the Technology Acceptance Model, which reflects human-computer interaction and explains how users adopt and accept new technologies. The problems of user acceptance of technology were first addressed by American scientist Fred Davis in his doctoral thesis (Davis, 1986). The author, basing his research on the behavior of users and their intentions to use new technologies, sought the essence of the relationship between the layout of a technological system and the user's acceptance of that system. The proposed model was presented as a construct of two variables, i.e., perceived usefulness and ease of use of the technology. In 1989, as a continuation of the research presented in his doctoral dissertation, Fred Davis's article "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology" (Davis, 1989) was written, in which the author, on a new scale, developed the study of the previously extracted two determinants of technology acceptance - perceived usefulness and perceived ease of practical use. Perceived Usefulness was defined as the degree of improvement in productivity and efficiency recognized by the user of new technologies. Perceived Ease of Use - as the degree to which the user believes that new technologies can be learned quickly and using them is easy. Davis's research indicated that a user's behavior and acceptance of a new technology is influenced more by the user's perception of the usefulness of the technology than the ease of use. In contrast, the perceived ease of use of a technology has a correlation with the perceived

usefulness of the technology and can be a direct motivation for the use of that technology. This is how the conclusion was drawn that perceived usefulness and ease of use determine users to use new technologies.

Many contemporary researchers recognize that individual user attitudes toward new technologies have a key impact on whether a technology is adopted or rejected. Thus, a researcher from Malaysia in the paper "A Literature Review on The Technology Acceptance Model" (Martin, 2022), a research team from Iran and the US M. Yadegari, S.D. Mohammadi, A.H. Masoumi, in the paper "Technology adoption: ananalysis of the major models and theories" (Yadegari et al., 2022), South African researchers M. Mkhonto and T. Zuva, in their paper "Technology Acceptance: A Critical Review of Technology Adoption Theories and Models" (Mkhonto, Zuva, 2024) offer a review of theories explaining how personal acceptance influences technology use behavior. Also in 2024 is a paper by F. Davis co-written with A. Granic: "The Technology Acceptance Model 30 Years of TAM" (Davis, Granić, 2024)., in which the authors describe the process of development of the TAM theory, conduct a review of research in the field from 2003-2023, and provide scenarios for future transformations of the theory. The overall result of the research conducted is that the success of any new technology is highly dependent on the level of acceptance of that technology by individual users. The research question remains whether we should consider the user as an individual unit or as a collection of units that make up society, and to what extent the individual unit influences the decision to reject or accept a new technology by society. This research problem, in fact, can also be reversed by examining the influence of society on an individual's behavior and the individual's ultimate acceptance or rejection of a new technology.

The most popular theories related to user adoption of technology in addition to Davis's theory (Technology Acceptance Model) include:

- Unified Theory of Acceptance and Use of Technology (UTAUT) - the theory shows the influence of expected technology performance, expected user effort, facilitating and social conditions on the level of acceptance of new technologies (Marikyan, Papagiannidis, 2023).
- Diffusion of Innovations (DOI) - the theory describes the ways in which new ideas and technologies spread between cultures (Rogers, 2003).
- Theory of Planned Behavior (TPB) - the theory examines the influence of subjective norms and behavioral intentions on the variability of actual human behavior (Ajzen, 1991).
- Social Cognitive Theory (SCT) - the theory emphasizes the role of observational learning and imitation in shaping patterns of human behavior, including acceptance of new systems and technologies (Bandura, 1986).

- Innovation Resistance Theory (IRT) - the theory distinguishes the reasons why an individual resists the introduction of systemic changes and new technologies (Ram, 1987).
- Task-Technology Fit (TTF) - this model views technology as a tool to perform a specific task and shows that the condition for acceptance of technology is that it fits the task, performed by the user (Goodhue, 1995).
- Expectancy-Value Theory (EVT) - the theory assumes that users' decisions are shaped by their expectations of the values obtained (Eccles, 1983).
- Cognitive Dissonance Theory- the main postulate of this theory is that people feel discomfort when there are contradictions between their beliefs and behaviors. By definition, people strive to reduce dissonance, which in turn can negatively affect the process of technology acceptance (Festinger, 1957).

An analysis of the above-mentioned theories allows us to identify the most important determinants of human acceptance of technology. First and foremost are the factors from Davis's theory, namely the perceived usefulness of the technology and the perceived ease of use. In addition to these two primary factors are:

- facilitating conditions (i.e., the technological infrastructure available to the user),
- user attitudes (in other words, the user's individual attitudes toward the technology, their experiences and preferences),
- trust in the technology and the level of perceived security (for example, protection of personal data, phishing scams or theft of money),
- socio-cultural factors (i.e., the level of acceptance of the new technology by the user's social environment, for example, acceptance of the technology by the user's peers, the influence of organizational culture on technology use, religious background) (Mkhonto, Zuva, 2024).

Identifying these determinants is itself the basis for understanding the reasons for adopting(accepting) or rejecting a new technology.

In their work based on the Technology Acceptance Model and other related TAM theories, researchers from around the globe are also undertaking research in the process of acceptance of modern technologies in specific areas of socio-economic life. Among the recent works emerging in this research area, we can highlight the following.

A study of the acceptance and use of e-money technology. The results of this work show that perceived ease of use and perceived usefulness affect people's attitudes toward the use of e-money, which in turn positively affects the actual use of e-money (Harnida, Mardah, 2023).

A study of the adoption process of technology based on the use of artificial intelligence to shape the supply chain (Venkatesh et al., 2023).

A study of factors influencing user behavioral attitudes toward the use of autonomous vehicles. The results of the study showed the influence of perceived usefulness, perceived ease of use and perceived innovation features on users' behavioral intentions to use autonomous vehicles (Yuen et al., 2020).

A study of the impact of perceived safety on the acceptance and use of autonomous vehicles in terms of the main demands of TAM. The results of the study indicated that the issue of perceived safety of autonomous vehicles has a significant direct impact on the user's intention in accepting this technology and dominates the perceived ease of use (Yao et al., 2023).

A study of cell phone user behavior influencing purchase decisions of these mobile devices. In this study, the researchers attempted to isolate the factors influencing the behavior of cell phone users in terms of their acceptance of brand switching and the technology used. The results of the conducted study showed that the factors that are key elements of the experience, namely the experience itself, expectations and emotions accompanying the experience form, on the one hand, resistance to changing the preferred and favorite brand, and on the other hand, they constitute a barrier to accelerated implementation of innovative solutions in the applied technology. This results in the fact that "loyalty" to a brand can limit the availability of new solutions, which is a guarantee for the company, but slows down the adaptation of innovative solutions (Reddy et al., 2022).

A study of user behavioral intentions in the acceptance of insideable technology in relation to non-medical implant information systems. The results of the study proved that acceptance of non-medical implant technology can be explained by perceived usefulness, perceived ease of use, social influence and perceived enjoyment (de Andrés-Sánchez et al., 2024).

A study of technology acceptance in educational settings. The study was directed at understanding user behavior in the context of voluntary use of modern educational technologies and indicates that attitudes toward the use of these technologies are explained by the relationship between perceived ease of use, perceived usefulness and intention to use (Or, 2024).

3. Research Methodology

3.1. Research Model

The research model presented in this study was oriented toward determining the intentions of modern college students to start their own e-business. It was assumed that these intentions depend, on the one hand, on the perceived value of running one's own e-business (HG1) and, on the other hand, on the level of acceptance of new technological solutions (HG2).

HG: Intentions to start one's own e-business dependent on perceived value (HG1) and level of acceptance of new technological solutions (HG2).

This approach allows us to define the main hypothesis as the effect of combining two determinants (Figure 1).

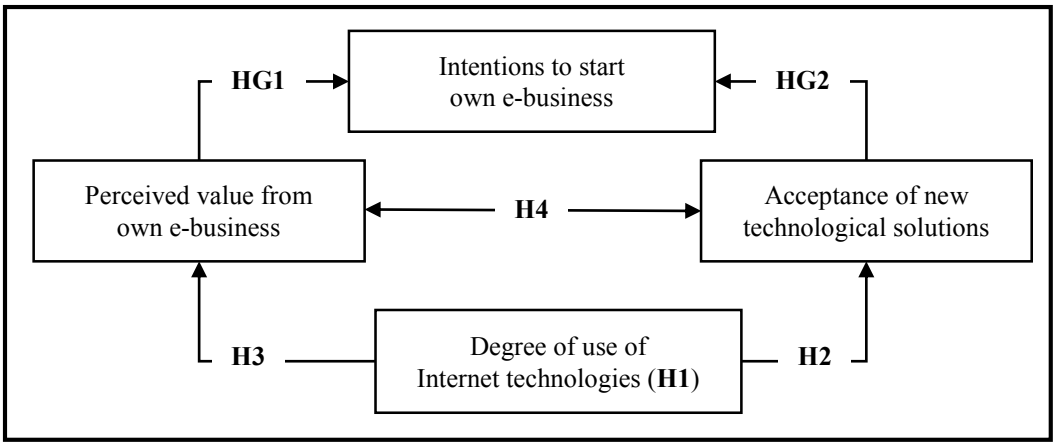


Figure 1. Complex systems of polygamous holes made from one cluster to several coal deposits.

In search of confirmation/rejection of the main hypothesis, research questions Q1 and Q2 and the hypotheses for answering these questions (H1-H2 and H3-H4) are formed.

Research question Q1: What level of technological skills and experience of using Internet technologies does the modern student have, and how does this affect his or her acceptance of new technological solutions?

H1. The modern student has a high level of technological skills and makes high use of Internet technologies in the educational process and daily life.

H2. The increase in the degree of use of Internet technologies contributes to increasing the technological skills and competencies of the modern student, which contributes to increasing the level of acceptance of new technological solutions in the student community.

Research question Q2: What is the perception of the modern student regarding e-business?

H3. The increase in the degree of use of Internet technologies raises the perceived value from one's e-business.

H4. The high level of acceptance of new technological solutions positively influences students' perceptions of the value added from starting their own e-business.

3.2. Research sample

The study presented here is qualitative in nature. Data was collected on the basis of a voluntary survey of students who studied at Polish universities in the summer semester of the 2023/2024 academic year and the winter semester of the 2024/2025 academic year. The total number of respondents was 340, which corresponds to the size of a representative sample (Table 1). The representative sample size was calculated using the sampling calculator assuming the following parameters: fraction size - 0.5; maximum error - 5%; confidence level α - between 93 and 94%; the number of students in higher education institutions in Poland in the academic year 2023/2024 - 1245153 people.

Table 1.
Profile of respondents

Parameter	Number of respondents	%
Gender		
male	167	49.12
female	165	48.53
other	3	0.88
prefer not to answer	5	1.47
Total	340	100.00
Generation		
Z (born 1995-2010)	327	96.18
Y (born 1981-1994)	10	2.94
X (born 1965-1980)	3	0.88
Year of study		
I	109	32.06
II	60	17.65
III	61	17.94
IV	66	19.41
V	44	12.94
Level of study		
Bachelor's degree	92	27.05
Master's degree	67	19.71
Uniform engineering studies	58	17.06
Uniform master's degree	123	36.18
Field of study		
Physiotherapy	123	36.18
Management	101	29.71
Economics	51	15.00
Electrical engineering	30	8.82
Data analytics in business	28	8.24
Tourism and recreation	5	1.47
Law	1	0.29
Production engineering and management	1	0.29

The students included in the research group are representatives of five Polish state universities (Opole University of Technology, Opole University, Warsaw University of Technology, Warsaw University, University of Economics in Katowice) from eight different majors: Physiotherapy (36.18%), Management (29.71%), Economics (15.00%), Electrical Engineering (8.52%), Business Data Analytics (8.24%), Tourism and Recreation (1.47%), Law (0.29%), Production Engineering and Management (0.29%). Students participating in the survey undertook studies in single master's (36.18%), bachelor's (27.05%), master's (19.71%), single engineering (17.06%). The survey covers students from all years of study. The vast majority of respondents refer to Generation Z (96.18%). Male gender was indicated by 49.12% of respondents, female by 48.53%, other by 0.88%, and 1.47% of respondents preferred not to answer this question. Further in the survey, the authors do not take into account the gender identity of respondents and do not focus on the field of study represented.

3.3. Research tools

The research tool was an anonymous online survey made in Google Forms. The research survey included closed questions. In order to evaluate individual phenomena related to the research area, the survey used a linear scale from 1 to 5 points. The process of filling out the survey took about 15-20 minutes. The research questionnaire included questions about the sociogeographical data of the respondents (shown in Table 1) to determine the silhouette of the research sample, as well as factual questions about the intentions of modern students to start their own e-business.

4. Results

4.1. Research question 1

Q1: What level of technological skills and experience of using Internet technologies does the modern student have, and how does this affect his/her acceptance of new technological solutions?

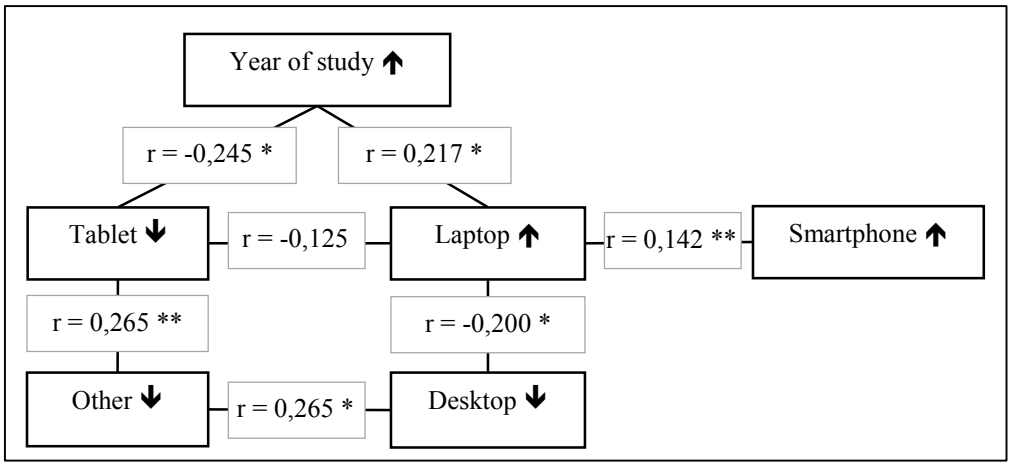
First, students were asked to answer the question, "How often do you use the Internet?" All respondents marked the answer "every day".

Another question "What devices do you usually use to access the Internet?" was to determine the preference of today's students for devices to access the Internet such as desktop, laptop, smartphone, tablet and others (respondents were asked to give ratings on a scale from 1 (almost never) to 5 (almost always)). The results of the survey indicate that currently the most popular device for accessing the Internet among students is a smartphone (the average rating was 4.75), followed by a laptop (rating of 3.21), in third place - a desktop computer (2.28), followed by a tablet and other devices (average rating of less than 2.00) (Table 2).

Table 2.
Evaluation of the degree of use of devices to access the Internet

Parameter	Device Type				
	Desktop	**Laptop**	**Smartphone**	**Tablet**	**Other**
Rating, points:	Number of respondents				
1	164	55	1	242	274
2	58	42	3	16	29
3	29	85	3	37	23
4	37	94	67	26	11
5	52	64	266	19	3
Average score, points	2.28	3.21	4.75	1.72	1.35
Sum of points earned by individual device types	775	1090	1614	584	460
Maximum possible sum of points for individual device types	1700	1700	1700	1700	1700
Percentage of points earned by individual device types, %	45.59	64.12	94.94	34.35	27.06
Sum of points earned by all device types	4523				
Usage structure of individual device types, %	17.14	24.10	35.68	12.91	10.17

An analysis of the distribution of ratings obtained by each type of device shows a consistency of opinion among respondents regarding the degree of use of smartphones (78% of respondents indicated that they almost always use a smartphone to access the Internet). However, in the case of laptops (the second most popular device), students' opinions were divided - a rating of "5" was given by 19% of respondents, ratings of "4" and "3" - 53%, and the remaining 28% put ratings of "2" and "1" respectively. Analysis of the structure of use of the mentioned devices shows that the frequency of use of a smartphone as a device to access the Internet i 1.5 times higher than that of a laptop and 2 times higher than that of a desktop computer. The results of the survey provide a basis for concluding that students' preferences for using devices to access the Internet change depending on the year (level) of study. Namely, the higher the year of study the more students are inclined to use the "symbiosis" of two devices - "smartphone-laptop" and the less they use tablets, desktop computers and other devices. In other words, in the course of studying, students strive to maximize efficiency in the combination of their mobility and the functionality of the devices they use (Figure 2).



* Statistical significance at the p = 0.01 level (p <= -0.14232 V p => 0.14232) at n = 340, where n is the number of respondents.

** Statistical significance at the p = 0.05 level (p <= -0.10760 V p => 0.10760) at n = 340, where n is the number of respondents.

Figure 2. Correlation between year of study and degree of use of devices to access the Internet.

The next group of questions the respondents were asked was to rate on a scale of 1 to 5 their level of experience in using digital devices and Internet technologies. Analysis of the responses shows that the vast majority of today's students (82%) refer themselves to experienced and very experienced users of computers and other digital devices. At the same time, 90% of all respondents indicated that they feel positive and very positive about their time using various Internet technologies. As for the ways in which Internet technologies are used in everyday life, to a great and very great extent these technologies are used by 40% of respondents for work, 75% for education, 85% for entertainment, 90% for communication with the environment, 29% for online shopping. As many as 87% of the surveyed students indicate the positive and very positive impact of online technologies on the educational process and that they use these

technologies for educational purposes daily or almost daily. In contrast, the frequency of daily online shopping was noted by only 9% of all respondents, online shopping several times a week was marked by 25% of respondents (Table 3).

Table 3.
Evaluation of the experience of using digital devices and online technologies

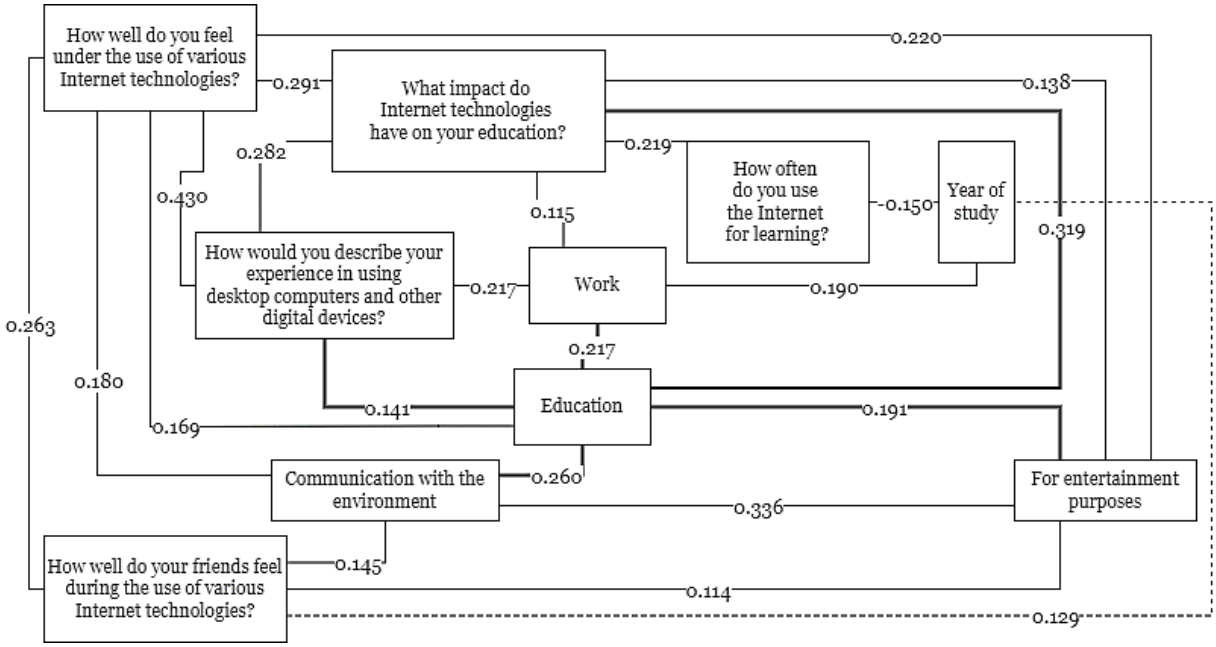
Question	Rating (points)	Number of people	Share, %
1. How would you describe your experience in using desktop computers and other digital devices?	Very experienced (5)	98	28.82
	Experienced (4)	182	53.53
	Moderately experienced (3)	58	17.07
	Beginner (2)	1	0.29
	No experience (1)	1	0.29
2. How well do you feel under the use of various Internet technologies?	Very positive (5)	188	55.29
	Positive (4)	118	34.71
	Neutral (3)	30	8.82
	Negative (2)	4	1.18
	Very negative (1)	0	0.00
3. How well do your friends feel during the use of various Internet technologies?	Very positive (5)	138	40.59
	Positive (4)	108	31.76
	Neutral (3)	84	24.71
	Negative (2)	9	2.65
	Very negative (1)	1	0.29
4. To what extent do you use Internet technologies in your daily life, i.e.:			
4.1. in the workplace	To a very great extent (5)	84	24.71
	To a great extent (4)	53	15.59
	In the medium degree (3)	84	24.71
	Below medium degree (5)	45	13.24
	To a very low degree (1)	74	21.75
4.2. for education	To a very great extent (5)	143	42.06
	To a great extent (4)	111	32.65
	To a medium degree (3)	74	21.76
	Below medium degree (5)	11	3.24
	To a very low degree (1)	1	0.29
4.3. for entertainment purposes	To a very great extent (5)	198	58.24
	To a great extent (4)	93	27.35
	To a medium degree (3)	39	11.47
	Below medium degree (5)	6	1.76
	To a very low degree (1)	4	1.18
4.4. to communicate with the environment	To a very great extent (5)	231	67.94
	To a great extent (4)	77	22.65
	To a medium degree (3)	28	8.23
	Below medium degree (5)	2	0.59
	To a very low degree (1)	2	0.59
4.5. for online shopping	To a very great extent (5)	41	12.06
	To a great extent (4)	57	16.76
	To a medium degree (3)	88	25.88
	Below medium degree (5)	58	17.06
	To a very low degree (1)	96	28.24
5. What impact do Internet technologies have on your education?	Very positive (5)	117	34.41
	Positive (4)	180	52.94
	Neutral (3)	41	12.06
	Negative (2)	2	0.59
	Very negative (1)	0	0.00

Cont. table 3.

6. How often do you use the Internet for learning?	Daily (5)	149	43.82
	Almost every day (4)	146	42.94
	Once a week (3)	30	8.82
	Rare (2)	13	3.83
	Almost never (1)	2	0.59
7. How often do you use the Internet to purchase goods and services?	Every day (5)	31	9.12
	Several times a week (4)	86	25.29
	Once a week (3)	112	32.94
	Rarely (2)	107	31.47
	Almost never (1)	4	1.18

Summarizing the results of the analysis of the responses to the questions on the evaluation of the experience of the modern student in the use of digital devices and Internet technologies we can conclude the following (Figure 3):

- there is a positive relationship between the level of experience with the use of Internet technologies and the use of these technologies in work and education, entertainment and online shopping,
- according to the opinion of students, Internet technologies reflect positively on the educational process,
- with each successive year of study, according to students, their technological skills increase, which in turn results in an increase in the degree of use of Internet technologies not only in the course of education and daily life, but also for the purpose of getting a job.



* Statistical significance at the p = 0.01 level (p <= -0.14232 V p = > 0.14232) at n = 340, where n is the number of respondents; Statistical significance at the p = 0.05 level (p <= -0.10760 V p => 0.10760) at n = 340, where n is the number of respondents.

Figure 3. Correlation* between the obtained answers to the questions on the evaluation of the experience of the modern student in the use of digital devices and Internet technologies.

The next question in the survey concerned the challenges and risks students faced when using Internet technologies. Respondents were asked to rate on a scale of 1 (hardly ever encountered) to 5 (very often encountered) the frequency of technical problems, problems related to access to technology, level of technological skills, cyber security, other problems (Table 4).

Table 4.
Rating of frequency of challenges and risks when using online technologies

Parameter	**Type of challenge or threat**				
	Technical problems	**Lack of access to technology**	**Lack of technological skills**	**Cybersecurity**	**Other**
Rating, points:	Number of respondents				
1	15	96	124	64	184
2	54	119	98	109	69
3	129	75	86	105	67
4	90	29	21	45	13
5	52	21	11	17	7
Average score, points	3.32	2.29	2.11	2.54	1.79
Sum of points obtained by individual challenge and threat types, points	1130	780	717	862	610
Maximum possible sum of points obtained in individual challenge and threat categories, points	1700	1700	1700	1700	1700
Level of perceived threat, %	66.47	45.88	42.18	50.71	35.88
Sum of points obtained from all challenge and threat categories, points	4099				
Structure of challenges and threats, %	27.57	19.03	17.49	21.03	14.88

Analysis of students' responses shows that the overall perceived level of challenges and risks associated with the use of Internet technologies is 48%.

$$OPWiZ = \frac{\sum S_i}{\sum M_i \times n} = \frac{4099}{1700 \times 5} \times 100 = 48.22$$

where:

OPWiZ – the overall perceived level of challenges and risks associated with the use of Internet technologies,

$\sum S_i$ – the sum of points obtained from all categories of challenges and threats, pt,

$\sum M_i$ – the maximum possible sum of points obtained from each category of challenges and threats, pts,

n – the number of categories of challenges and threats related to the use of Internet technologies studied.

The biggest challenge at the time of using Internet technologies for our respondents is technical problems, their share in the structure of all challenges is almost 28% (78% of the surveyed students put a rating from 3 to 5, the average rating from the question was 3.32, and the level of this threat from the students' point of view is almost 67%). The second most important problem is considered by respondents to be cyber security (share of the challenge structure - 21%, average rating from the question - 2.54, threat level - 51%). Lack of access to technology ranks third (19% - share of the challenge structure). Lack of technological skills ranks fourth (18% - share of the challenge structure), but it is noteworthy that the majority of respondents (91%) rated this threat as insignificant and put ratings between 1 and 3 (Table 4). In other words, students are aware of the occurrence of various technological challenges, but are not afraid of these challenges due to the high level of technological skills in their own self-assessment.

In the next part of the survey, the respondents were asked to self-assess their ability to accept new technological solutions. On a scale of 1 to 5, students were asked to answer five questions (Table 5).

Table 5.
Self-assessment of students' ability to accept new technological solutions

Parameter	**Questions**				
	How do you rate your ability to obtain new competencies in technological skills?	**How do you rate your colleagues' ability to obtain new competencies in technological skills?**	**How often do you seek out new information and resources on technology?**	**How good are you at solving problems related to new technology?**	**How comfortable do you feel using new technology to create new things and solve problems?**
Rating, points:	Number of respondents				
1	4	3	2	3	2
2	24	20	53	24	13
3	145	137	142	149	125
4	108	139	103	122	125
5	59	41	40	42	75
Average score, points	3.57	3.57	3.37	3.52	3.76
Total points obtained according to individual questions	1214	1215	1146	1196	1278
Sum of points obtained from all questions	6049				
Maximum sum of points to be obtained by individual questions	1700	1700	1700	1700	1700
Share of points obtained by individual questions, %.	71.41	71.47	67.41	70.35	75.18

Analysis of the responses indicates that today's student shows a high level of ability to acquire new technological competence. 92-93% of all respondents gave a positive assessment of their ability and the ability of their peers to obtain new technological competencies, with an average of 51% rating their ability at 4 and 5. 84% of all respondents indicated that they often seek new information and technological solutions, with 42% putting ratings of 4 and 5 (i.e., often and very often). 92% of all respondents indicated that they are good at solving problems with new technology, and 96% of respondents indicated that they feel comfortable using new technology to create new things and solve problems. Summarizing the answers to the questions in this pool we can conclude that the modern student in his or her own assessment has a high level of acceptance of new technological solutions.

4.2. Research question 2

Q2: What is the perception of the modern student regarding e-business?

In search of an answer to the second research question, students were asked whether they, in general, think about the future of technology and e-business. A positive answer to this question was given by nearly 60% of all respondents. On the other hand, only 9% of the students surveyed indicated that they are already involved in e-business, while 18% said that they definitely want to start their own e-business in the future, 43% of the respondents are thinking about starting their own e-business, but are not sure. At the same time, the vast majority of students, i.e., 98%, have positive attitudes toward the development of Internet technology and e-business, out of these, 50% of respondents are sure that e-business has a positive impact on society, and only 5% say that e-business has or may have a negative impact on the further development trends of society.

In evaluating the benefits of e-business, students indicated first and foremost convenience of use (average rating - 4.47) and availability of goods/services/forms of payment (rating - 4.34), in third place was a wide selection of goods/services/solutions (rating 4.23), and in fourth place was adequate prices (rating - 3.83) (Table 6).

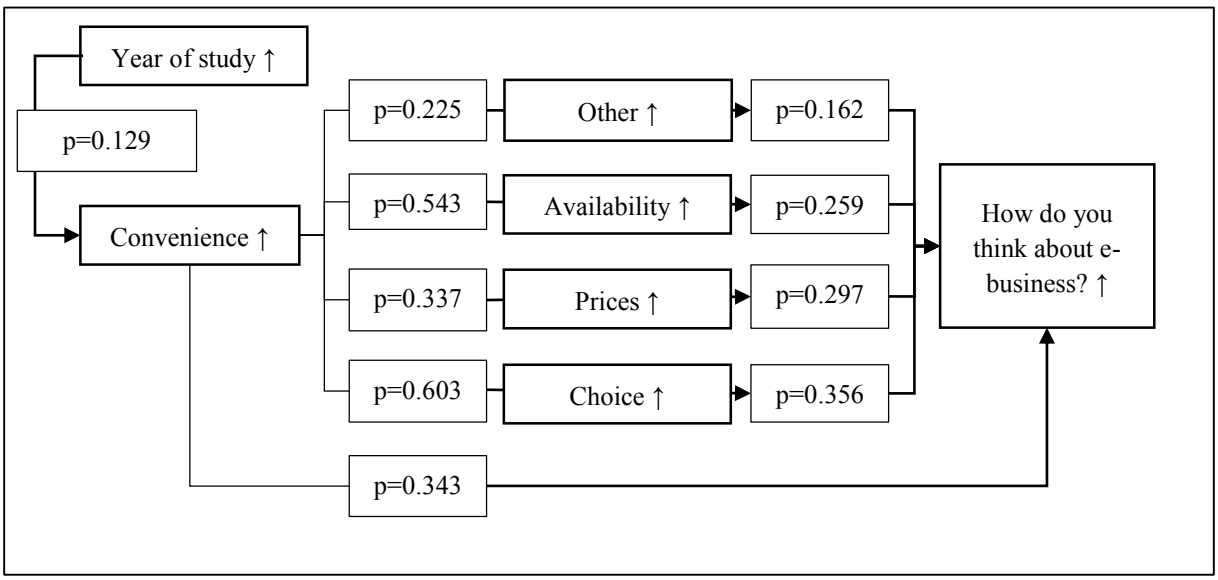
Table 6.
Evaluation of the benefits of e-business in the opinion of the modern student

Indicators	Type of benefits of e-business				
	Convenience	**Choice**	**Prices**	**Availability**	**Other**
Rating, points:	Number of respondents				
1	3	1	4	2	107
2	3	10	16	10	33
3	28	51	106	41	88
4	103	125	122	103	52
5	203	153	92	184	60
Average score, points.	4.47	4.23	3.83	4.34	2.78
Sum of points obtained within the distinguished types of benefits, points.	1520	1439	1302	1477	945
Maximum possible sum of points obtained under separate types of benefits, points.	1700	1700	1700	1700	1700

Cont. table 6.

Share of points collected, %	89.41	84.65	76.59	86.88	55.59
Sum of points obtained from all evaluations, points.	6683				
Structure of perceived benefits from e-business, %.	22.74	21.53	19.48	22.1	14.14

In conclusion, we can say that the modern student generally has positive attitude towards e-business, perceives its added value and highly appreciates the benefits of this economic phenomenon (Figure 4).



* Statistical significance at the p = 0.01 level (p <= -0.14232 V p => 0.14232) with n = 340, where n is the number of respondents.

Figure 4. Statistically significant relationship* between year of study and perceived benefits from e-business and students' opinion regarding e-business.

An analysis of the correlation coefficients calculated from the students' responses indicates that with an increase in the year of study (and that is, the experience of the students and the degree of use of Internet technologies by the students - hypotheses H1 and H2, which were confirmed in the previous part of this paper) there is an increase in the sense of comfort from e-business, which is highly dependent on "Choice", "Price" and "Availability", which in turn translates into an increase in students' positive attitudes toward e-business.

Another pool of questions in the survey concerned the values that students may perceive from starting their own e-business (Table 7).

Table 7.
Perceived values from starting one's own e-business according to today's students

Question		Average rating	Response structure. %				
Question code	Question content		1	2	3	4	5
I. Introductory questions							
QK1.1	To what extent are you interested in starting your own business?	3.40	8.82	14.41	30.29	20.59	25.89
QK1.2	What is the likelihood that you will start your own e-business in the next five years?	2.58	23.24	28.53	25.59	12.64	10.00
II. Material (financial) values							
QK2.1	How important is it to you to earn a high income from your own business?	4.29	0.88	2.35	13.82	32.65	50.30
QK2.2	How confident do you feel about managing the finances of your own e-business?	3.18	4.12	17.06	42.35	29.41	7.06
QK2.3	How likely is it that starting an e-business will provide you with financial security? *	3.07	4.41	17.94	48.24	25.29	4.12
III. Intangible values (personal development, self-fulfilment, self-confidence)							
QK3.1	How important is it for you to be your own boss and have control over your work life?	3.88	3.82	9.71	19.71	28.24	38.52
QK3.2	Do you think starting an e-business is a difficult but rewarding experience?	3.76	2.35	5.88	31.47	34.41	25.89
QK3.3	How much satisfaction do you think you would derive from starting your own e-business?	3.58	6.76	10.59	24.41	34.12	24.12
QK3.4	What is the likelihood that starting an e-business would make you feel fulfilled and successful?	3.44	7.65	11.47	29.71	32.06	19.11
QK3.5	How confident do you feel about building a strong brand and reputation for your e-business?	3.41	4.71	13.53	37.35	25.29	19.12

* Choice options: 1 - from 0 to 20%; 2 - from 21 to 40%; 3 - from 41 to 60%; 4 - from 61 to 80%; 5 - from 81 to 100%.

Analyzing the questions from this pool we can deduce that in almost 77% of the surveyed students indicated that they were interested in starting their own business (ratings of 3, 4 and 5), and 22.64% of the surveyed students said that there was a fairly high probability (61% and above) of starting their own e-business in the next five years.

The greatest value that today's students perceive from starting their own e-business is financial, namely "earning a high income from their own business" (average rating from respondents' answers - 4.29, 83% of respondents put ratings of 4 and 5). At the same time, 78% of students indicated that they feel confident about managing the finances of their own e-business and setting up an e-business will provide them with financial security.

The second most important value for students is the opportunity to be their own boss and have control over their own work life (average score - 3.88). Third place is occupied by the satisfaction one can have from setting up one's own e-business (rating - 3.76). It is noteworthy that in assessing the level of satisfaction, 68% of respondents gave ratings of 4 and 5. Almost 51.17% of respondents mark a high level of probability (from 61 to 100%) that starting your own e-business will make you feel fulfilled and professionally successful. At the same time, 82% of respondents feel good about building a strong brand and reputation for their e-business.

Table 8 shows correlation coefficients between values perceived by modern students from starting their own e-business.

Table 8.
*Correlation coefficients between values perceived by modern students from starting their own e-business**

Question code	I. Introductory questions		II. Material (financial) values			III. Intangible values (personal development, self-fulfilment, self-confidence)				
	QK1.1	**QK1.2**	**QK2.1**	**QK2.2**	**QK2.3**	**QK3.1**	**QK3.2**	**QK3.3**	**QK3.4**	**QK3.5**
QK1.1	1	0.587	0.395	0.447	0.317	0.500	0.221	0.492	0.440	0.463
QK1.2	0.587	1	0.154	0.370	0.337	0.354	0.216	0.511	0.508	0.507
QK2.1	0.395	0.154	1	0.290	0.201	0.386	0.208	0.349	0.327	0.314
QK2.2	0.447	0.370	0.290	1	0.368	0.274	0.215	0.392	0.347	0.451
QK2.3	0.317	0.337	0.201	0.368	1	0.196	0.177	0.317	0.360	0.287
QK3.1	0.500	0.354	0.386	0.274	0.196	1	0.316	0.440	0.438	0.480
QK3.2	0.221	0.216	0.208	0.215	0.177	0.316	1	0.405	0.359	0.328
QK3.3	0.492	0.511	0.349	0.392	0.317	0.440	0.405	1	0.694	0.586
QK3.4	0.440	0.508	0.327	0.347	0.360	0.438	0.359	0.694	1	0.581
QK3.5	0.463	0.507	0.314	0.451	0.287	0.480	0.328	0.586	0.581	1

* Statistical significance at the p = 0.01 level (p <= -0.14232 V p => 0.14232) with n = 340, where n is the number of respondents.

Significance analysis of the correlation coefficients calculated on the basis of the obtained answers to the questions on perceived values from starting one's own e-business (Table 8) indicates that there is a statistically significant relationship between the desire to start an e-business and perceived tangible and intangible values. In other words, when deciding to start their own e-business, students expect not only good financial results, but both professional success and personal development.

5. Discussion and Conclusions

5.1. Theoretical Contributions

The conducted research dedicated to distinguishing the intentions of starting one's own e-business in the contemporary student environment focuses on the search for correlations between the actual degree of use of Internet technologies in the educational process and daily life, the level of students' acceptance of new technological solutions, and the perceived value from running one's own e-business. The research confirmed that the highlighted three elements play a key role in the intentions of starting one's own e-business in the student environment. The results obtained contribute to the development of the TAM (Technology Acceptance Model) theory continuing the research in the field of "human-computer" interaction and explaining how the modern student makes a decision about starting his own e-business.

The search for answers to the first research question (Q1: What level of technological skills and experience of using Internet technologies does the modern student have, and how does this affect his or her acceptance of new technological solutions?) led to the following conclusions:

1) The conducted assessment of the level of use of devices to access the Internet (Table 2, Figure 1) and the assessment of the experience of using digital devices and Internet technologies (Table 3) confirm hypothesis H1. The modern student has a high level of technological skills and makes high use of Internet technologies in the educational process and daily life.
2) The correlation analysis between the answers to the questions to evaluate the experience of the modern student in using digital devices and Internet technologies according to the year of study (Figure 2), the evaluation of the frequency of various types of challenges and risks when using Internet technologies (Table 4), and the self-assessment of the students' ability to accept new technological solutions (Table 5) confirm hypothesis H2. The increase in the degree of use of Internet technologies contributes to the technological skills and competencies of the modern student, which results in a high level of acceptance of new technological solutions in the student community.

The search for answers to the second research question (Q2: What is the perception of the modern student regarding e-business?) allows us to conclude that the modern student has good intentions with regard to starting their own business for the reason that they perceive great benefits and values from e-business.

The combination of the analysis of the answers to the first and second research questions made it possible to confirm hypothesis H3 and H4, namely, the increase in the degree of use of Internet technologies increases the perceived value from own e-business (H3) and the high level of acceptance of new technological solutions positively affects the perceived values from starting own e-business (H4). This finally leads to the conclusion that the intention to start own e-business depends on the perceived value and level of acceptance of new technological solutions.

5.2. Practical Implications

The study conducted provides practical implications first and foremost for higher education institutions, namely for those responsible for shaping curricula, and directly for academics implementing these curricula.

First, educational programs at universities must include subjects aimed at improving digital skills, and all classes conducted must be oriented on the use of Internet technologies. Such an approach can benefit all students regardless of their field of study and year of study.

Second, in the course of teaching, it is crucial to emphasize the value provided by modern Internet technologies and the direct process of running one's own business including e-business. Accordingly, it is advisable at universities, regardless of their specialization, to shape and implement teaching programs aimed at disseminating the benefits of new technological solutions.

Third, it is crucial when shaping the curricula of higher education institutions to adapt specialized technological solutions to different fields of study. In such a way, the learning programs developed and implemented will raise the level of acceptance of new technological solutions in the student community and thus contribute to perceiving the value of starting one's own e-business.

6. Limitations and Future Research

The conducted study has some limitations. First of all, the study was conducted only at Polish universities. Therefore, subsequent studies may include students from other EU areas, i.e. countries with similar socio-economic conditions, a similar system of organization of higher education and a similar level of technological development. These studies can further confirm the results obtained or supplement them. On the other hand, the next stage may be research conducted in non-EU countries with a different economic system and a different way of organizing higher education. Such research will make it possible to distinguish the peculiarities of intentions to start one's own e-business in student communities operating under different technological conditions.

In addition, another study regarding the intentions of modern college students to start their own e-business could take into account behavioral factors, i.e. the behavioral styles of modern students, which affect both the level of acceptance of new technological solutions and the perceived value from their own e-business.

Structured in this way, future research can bring additional development in TAM and provide further practical implications not only for universities as educational institutions, but also directly for students as individuals shaping their future.

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THE ROLE OF REGIONAL INNOVATION SYSTEMS IN ACHIEVING THE SDGS: EVIDENCE FROM SELECTED AGRICULTURAL REGIONS IN CENTRAL AND EASTERN EUROPEAN COUNTRIES

Bogdan WIERZBIŃSKI

University of Rzeszów; bwierzbinski@ur.edu.pl, ORCID: 0000-0002-6324-6265

Purpose: The motivation behind this research stems from the need to deepen the understanding of how Regional Innovation Systems (RIS), as place-based innovation structures, can contribute to sustainable development outcomes in regions less industrialised and agriculture-dependent.
Design/methodology/approach: This study applies a comparative case study approach to examine the role of RIS in supporting the implementation of selected Sustainable Development Goals (SDGs 2, 8, 9, 11, 12) in rural and agriculturally intensive regions of Central and Eastern Europe. Multi-criteria and multi-method approach enables identification of key barriers and enablers for aligning RIS activities with sustainable development priorities in rural areas.
Findings: The analysis revealed that while all three countries use similar EU innovation frameworks, Poland demonstrates the most effective integration of RIS with rural SDG implementation, while Hungary and Romania face significant structural, governance, and institutional challenges that limit their impact.
Research limitations/implications: This study has several limitations that should be acknowledged. First, the analysis is constrained by the availability and comparability of regional secondary data in Central and Eastern European (CEE) countries. Second, the concept of Regional Innovation Systems (RIS) is inherently context-dependent and difficult to quantify uniformly.
Practical implications: Strengthening Institutional Capacity in Rural Regions to improve RIS performance in less-developed areas, it is essential to invest in local innovation infrastructure, support networks (e.g., innovation hubs, agricultural knowledge centres) and human capital development tailored to local needs and sustainability challenges.
Social implications: The development of Regional Innovation Systems in agricultural regions of Central and Eastern Europe has significant social implications, particularly in promoting more inclusive and equitable rural development**.** By improving access to innovation, education, and technological support, RIS can help reduce territorial disparities and improve social cohesion.
Originality/value: This paper offers a novel comparative perspective on how Regional Innovation Systems in Poland, Hungary, and Romania contribute to rural SDG implementation, providing valuable insights for policymakers, researchers, and regional development actors focused on sustainable and inclusive innovation.
Keywords: Regional Innovation Systems, Sustainability, Sustainable Development Goals, rural areas.
Category of the paper: Case study, Viewpoint.

1. Introduction

The purpose of this article is to examine how Regional Innovation Systems (RIS) support the implementation of selected Sustainable Development Goals (SDGs) in regions with a strong agricultural structure, with a particular focus on rural areas of Eastern Poland. Despite their significant natural and productive potential, these regions often face structural challenges such as limited economic diversification, underdeveloped infrastructure, and outmigration of human capital. In this context, RIS—understood as mechanisms that coordinate collaboration between science, business, public administration, and civil society—can play a crucial role in fostering innovative and sustainable development tailored to local conditions.

The selection of SDG 2 (Zero Hunger), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) is based on their direct relevance to the challenges and opportunities characteristic of rural areas. These goals reflect the need to ensure food security and agricultural development (SDG 2), create decent jobs and strengthen local economies (SDG 8), and develop infrastructure and technologies (SDG 9). They also encompass efforts to improve the quality of life in small towns and villages (SDG 11) and promote a more efficient and responsible use of resources (SDG 12). The article assumes that the synergistic use of RIS can contribute to more effective achievement of these goals, while enhancing social cohesion and long-term competitiveness of rural regions (tab. 1).

Table 1.
The main proposal to examine the goals

SDG goals	**The main proposal of the SDG goals chosen**	
SDG 2 – Zero Hunger	Food security and improved nutrition, and promote sustainable agriculture for all	(Huang et al., 2020); (D'Adamo, Rossi, 2025); (Miao et al., 2025); (Lehoux et al., 2018); (Leal Filho et al., 2022); (Cheshmehzangi, Zou, 2024); (Martinez-Gutierrez et al., 2025), (Godlewska-Majkowska et al., 2025), (Czupryna-Nowak, 2024)
SDG 8 – Decent Work and Economic Growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work for all	
SDG 9 – Industry, Innovation and Infrastructure	Resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation	
SDG 11 – Sustainable Cities and Communities	Cities and human settlements are inclusive, safe, resilient, and sustainable	
SDG 12 – Responsible Consumption and Production	Sustainable consumption and production patterns by improving resource efficiency and reducing waste	

Note. (Leal Filho et al., 2022); (Cheshmehzangi, Zou, 2024); (Czupryna-Nowak, 2024), (Godlewska-Majkowska et al., 2025).

Source: Own research.

The importance of Regional Innovation Systems (RIS) for rural areas' development can be understood through the lens of selected Sustainable Development Goals (SDGs), which reflect key challenges and growth potential. In this context, RIS can play a strategic role as a tool to integrate knowledge, policy, and local resources in the pursuit of sustainable development.

SDG 2 – Zero Hunger – Rural areas, especially those with a strong agricultural profile, are directly involved in food production. RIS can support innovations in agriculture, agrotechnology, agribusiness and food logistics, thus increasing efficiency (Klerkx, Rose, 2020; Ramirez et al., 2019), quality, and sustainability of agricultural production while reducing food losses (Drabik et al., 2019). SDG 8 – Decent Work and Economic Growth Peripheral regions often face issues such as unemployment, labour migration, and limited economic diversification (Wurster, Ladu, 2020; Rodríguez-Pose, 2018). RIS can support the development of small companies, rural entrepreneurs and the creation of new jobs through innovative business models, particularly in the agri-food sector, tourism, and local services (Jiang et al., 2019). SDG 9 – Industry, Innovation and Infrastructure Rural areas often suffer from underdeveloped infrastructure and a weak network of institutions supporting innovation (Townsend et al., 2017). RIS can act as integrators of local actors (Asheim, Isaksen, 2002), enhance innovation infrastructure (e.g., incubators, competence centres, knowledge networks), and support the adoption of modern technologies in traditional sectors. SDG 11 – Sustainable Cities and Communities. Although this goal mainly applies to urban areas, its components—such as spatial planning, mobility, energy, and access to services—are equally important for smaller towns and rural regions. RIS can support smart and sustainable land-use strategies, as well as initiatives such as the "smart village" (Godlewska-Majkowska et al., 2025; Czupryna-Nowak, 2024). SDGs 12 – Responsible Consumption and Production Production and consumption in rural areas can become more sustainable through innovations in precision agriculture (Silva, Gerhard, 2025). Recent studies show that RIS plays a vital role in localising and operationalising the SDGs through territorial innovation, knowledge diffusion, public-private cooperation, and smart specialisation strategies. These systems improve regional competitiveness, enable circular economies, promote sustainable infrastructure, and facilitate community-driven innovation ecosystems. They also provide targeted responses to food security, urban sustainability, and inclusive economic growth—each directly related to SDGs 2, 8, 9, 11 and 12.

2. Methodology

Selection of Countries to Study the Impact of Regional Innovation Systems (RIS) on the implementation of selected Sustainable Development Goals (SDGs) in regions with a strong agricultural structure. Using a mixed-method approach that combines comparative analysis and case studies, the research explores how institutional arrangements, innovation support mechanisms, and knowledge networks in less-developed regions contribute to sustainable transformation. The selection of countries to study the impact of Regional Innovation Systems (RIS) on the implementation of selected Sustainable Development Goals (SDGs) in regions

with a strong agricultural structure should be based on clearly defined criteria that allow a comparable and reliable analysis. The following is a proposed methodology to select countries for the study.

Geographical and Macro-Regional Criteria

Focus on countries in Central and Eastern Europe (CEE), such as Poland, Hungary, Slovakia, Czech Republic, Romania, Bulgaria, Lithuania, Latvia, Estonia, Croatia, and Slovenia.

These countries share the following characteristics:

- A similar history of economic transformation after 1989,
- Structural challenges in the development of rural areas,
- Membership in the EU (providing access to common RIS and SDG programmes),
- Significant agriculture or employment in peripheral regions.

The following matrix presents the selection criteria to identify countries to be included in the study of the role of Regional Innovation Systems (RIS) in supporting the implementation of selected Sustainable Development Goals (SDG 2, 8, 9, 11, 12) in areas with a strong agricultural structure in Central and Eastern Europe. Based on the evaluation using selected criteria, three countries were chosen for further comparative analysis. The methodology of country selection based on the Likert scale (1-5) enables a transparent and comparative assessment of multidimensional indicators. Three countries were selected for analysis (tab. 2).

Table 2.
Country Selection Matrix (scale: 1 = low level, 5 = high level)

Country	Agriculture share in the economy	Rural population share	RIS maturity	Availability of regional data	Progress in SDG implementation	TOTAL
Poland	4	4	5	4	4	21
Romania	5	5	3	3	3	19
Hungary	3	3	4	3	4	17
Czechia	1	1	4	4	5	15
Lithuania	4	3	3	3	3	16
Bulgaria	3	1	2	3	2	11
Slovakia	1	5	3	3	4	16

Notes: Agriculture, Forestry and fishing, value added **(%GDP):** In 2023-24, agriculture had the largest share of GDP in Romania (3.3%) and Bulgaria (2.1%), a moderate share in Lithuania (2.6%) and Hungary (2.4%), and the smallest in Poland (2.6%), Slovakia (2.0%), and Czechia (1.5%), reflecting the diverse economic structures of the region; **Rural population (% of total population)** In 2024, Slovakia (45.6%) and Romania (44.6%), followed by Poland (39.7%) and Lithuania (31.0%). In Hungary, the rural population accounted for 27.3%, in Czechia 25.3%, while the smallest share was observed in Bulgaria (23.4%) (World Bank Open Data, n.d.); **RIS maturity (RIS maturity is often assessed along several dimensions: Governance structures, University-industry-government collaboration, Integration with EU funds, etc.)** Poland, demonstrate higher RIS maturity through decentralization, strong institutions; Czechia, Hungary and partly Lithuania, Slovakia, Romania represent medium maturity with existing but weakly coordinated structures; while Bulgaria show lower maturity due to fragmented implementation, low institutional capacity, and limited stakeholder engagement; **Availability of regional data:** The availability of regional data across Central and Eastern Europe exhibits significant variation, with Poland and Czechia offering comprehensive and systematically disaggregated statistics, Hungary, Lithuania, Slovakia Romania and Bulgaria providing moderately developed but partially centralized datasets, displaying the lower levels of data granularity; **Progress in SDG implementation** among the selected Central and Eastern European countries reflects a gradient of progress, with Czechia leading due to strong and consistent performance across

economic, social, and environmental goals. Poland and Hungary occupy middle positions, displaying mixed results—stronger in economic indicators but lagging in environmental and social areas. Slovakia and Lithuania follow, showing solid progress in aligning national policies with EU SDG strategies, particularly in health and education. Romania ranks lower due to persistent challenges in infrastructure, inequality, and governance, while Bulgaria is placed last, consistently underperforming across multiple SDG dimensions, especially in environmental and institutional indicators (Širá et al., 2021), (Ionescu et al., 2021).

Source: Own research.

Poland: Highest overall score; strong agricultural sector and well-developed RIS structure, especially in Eastern Poland; high availability of regional data. Romania: a very high share of agriculture and rural population, less developed RIS – allows identifying barriers and development opportunities. Hungary: Average level of progress of RIS and SDG, agricultural profile in some regions – serves as a good reference point for comparison with Poland and Romania. Selected countries and regions for analysis (tab. 3).

Table 3.
The main Rural Regions taken into consideration for Case Studies

Country	Example Rural Region	RIS Status	Agricultural Profile
Poland	Lubelskie, Podkarpackie, Świętokrzyskie	Strong RIS infrastructure	Extensive agri- & bio-economy
Hungary	Southern Great Plains (Dél-Alföld)	Mid-level RIS, active universities	Grain, horticulture, livestock
Romania	North-East, South Muntenia	Weak RIS, opportunity for growth	Rural majority, subsistence agriculture

Note. (Adamowicz, 2021), (Serbanica, 2021), (Fieldsend et al., 2017), (Borychowski et al., 2020), (Borychowski et al., 2020).

Source: Own research

Poland and Romania have a large share of family farms, with Poland distinguished by fruit-growing, while Romania stands out for maize and sunflower cultivation. Hungary is concentrated on the Great Hungarian Plain, where agriculture is the most developed (vegetable production, cereals, fruits).

Research Questions:

1. Which components of regional innovation systems (institutions, policies, infrastructure) are most relevant for supporting agriculture and the food sector in the context of SDG 2 – Zero Hunger?
2. To what extent do RIS contribute to the creation of decent jobs and the stimulation of economic growth (SDG 8) in rural regions?
3. How and to what extent do RIS facilitate the development of infrastructure, innovation, and industry (SDG 9) in peripheral rural areas?
4. What forms of RIS support enable the implementation of sustainable and “smart” rural community development strategies (SDG 11)?
5. In what ways do RIS promote responsible consumption and production (SDG 12) by supporting technological, social, and organizational innovations at the local level?

Concluding questions:

6. How do the strategies and effectiveness of RIS vary across selected Central and Eastern European countries (e.g. Poland, Romania, Hungary) in supporting the implementation of the SDG in rural areas?
7. What are the key barriers and enablers for effectively aligning RIS activities with the SDG agenda in agriculturally oriented regions?

The set of research questions directly operationalizes emphasises the role of localised learning, institutional structures, and cooperative networks in enhancing regional competitiveness and economic development (Pidorycheva et al., 2020) Regional Innovation Systems (RIS) – *are analytical frameworks describing how regional actors interact to foster innovation, whereas Research and Innovation Strategies for Smart Specialisation (RIS3) are EU policy instruments that operationalise these dynamics by prescribing place-based priorities for investment and development* (Lopes et al., 2019) — in implementing the 2030. Agenda in agricultural regions of Central and Eastern Europe, and the set of research questions directly operationalises this perspective: identifies which RIS components—institutions, policies, and infrastructure—most strongly support agriculture and food security (SDG 2), assesses the degree to which they translate into decent work and economic growth in rural areas (SDG 8), and how they shape the development of infrastructure, innovation, and industry in peripheral rural areas (SDG 9). The questions also address forms of RIS support that facilitate the implementation of sustainable and "smart" community development strategies (SDG 11) and mechanisms that promote responsible consumption and production through technological, social, and organisational innovations at the local level (SDG 12). The comparative perspective (Poland, Romania, Hungary) provides information that reveals differences in RIS strategies and effectiveness in the context of the implementation of the SDG, while the analysis of barriers and enabling factors identifies the conditions to effectively align RIS activities with the sustainable development agenda in agricultural regions.

3. Discussion in relation to the research questions

Which components of regional innovation systems (institutions, policies, infrastructure) are most relevant for supporting agriculture and the food sector in the context of SDG 2 – Zero Hunger?

Institutions are central to agricultural innovation, with research centres, universities, and advisory services developing locally adapted technologies such as drought-resistant crops and precision farming. Cooperatives and producer organisations support knowledge sharing, collective investment, and stronger market positions, while financial institutions provide credit and insurance to enable adoption. Effective policies further drive sustainable agriculture by

promoting R&D, public–private partnerships, agricultural education, and digital skills, while trade policies should ensure fair market access for small producers. Climate adaptation strategies are also critical for environmentally friendly practices. Finally, physical and digital infrastructure underpins innovative systems: transport networks, storage facilities, irrigation, and renewable energy improve efficiency and sustainability, while internet access and mobile tools connect farmers to forecasts, prices, and expertise. Industrial parks and hubs foster collaboration between science, business, and producers (tab. 4).

Table 4.
Regional innovation systems in the context of SDG 2 – Zero Hunger (SWOT analysis)

SWOT Type	Poland	Hungary	Romania
Strengths	Strong research base; well-developed advisory system; coherent digitisation policies; solid infrastructure.	Growing investment in digitalisation and agricultural modernisation; policy support and access to EU funding.	Strong involvement in EU programmes; increasing role of NGOs and private advisory; large infrastructure investments.
Weaknesses	Uneven collaboration between science and practice; limited infrastructure in rural areas.	Weak advisory system and limited knowledge transfer; low level of regional collaboration.	Institutional incoherence; poor infrastructure in many regions.
Opportunities	Potential to enhance knowledge transfer; development of precision agriculture and renewable energy supported by EU funds.	Development of digital infrastructure; better use of the potential of agricultural universities.	Reduction of regional disparities; increase in technology transfer.
Threats	Risk of marginalising small farms; outmigration of rural youth.	Farm fragmentation; underinvestment in rural areas.	Dependence on EU funding; difficulties in implementing policies locally.

Source: Own research.

Achieving Sustainable Development Goal 2 – Zero Hunger – requires effective regional innovation systems (RIS) that integrate institutional, policy, and infrastructure components to support agriculture and food systems. In **Poland**, RIS efforts have progressed through initiatives such as Smart Villages, which strengthen collaboration between research institutions and local producers (Adamowicz, Zwolińska-Ligaj, 2020; Adamowicz, 2021). Yet, rural ICT and logistics infrastructure remain uneven. **Romania** faces more systemic weaknesses of RIS, including fragmented institutional coordination and underdeveloped rural infrastructure (Bădîrcea et al., 2025). Nonetheless, European Regional Development Fund (ERDF) — *one of* the main financial instruments of the European Union's Cohesion Policy, established to reduce economic disparities between regions by funding infrastructure, innovation, environmental protection, and support for small and medium-sized enterprises (SMEs) in less developed areas (Bădîrcea et al., 2025b) — supported programs have recently targeted innovation in sustainable agriculture. **Hungary** shows stronger institutional capacity, supported by national agricultural research centers and active S3 in food and bioeconomy (Shvets et al., 2023). However, regional disparities and limited integration of environmental objectives remain. Across all three countries, key RIS components for SDG 2 include robust research-practice linkages, regionally

aligned agri-innovation policies, and improved rural infrastructure such as irrigation and digital access. Strengthening governance and targeted funding is essential to transforming the agricultural sector into a more resilient and food-secure system in Central and Eastern Europe.

To what extent do RIS contribute to the creation of decent jobs and the stimulation of economic growth (SDG 8) in rural regions?

Regional Innovation Systems (RIS) have increasingly become essential mechanisms in promoting SDG 8 — "decent work and economic growth" — particularly in rural regions across Poland, Hungary, and Romania (tab. 5). These systems, characterized by coordinated interactions among local actors (universities, firms, governments, etc.), foster innovation-led development, reduce regional disparities, and stimulate job creation. However, the degree of impact varies due to national policy frameworks, historical legacies, structural inequalities, and institutional readiness.

Table 5.
Sustainable Development Goal 8 – Decent Work and Economic Growth (SWOT Analysis)

SWOT Dimension	Poland	Hungary	Romania
Strengths	Strong EU funding absorption; Decentralized RIS; Agricultural base for agri-tech innovation.	Established RIS policy frameworks; Industry-agriculture innovation potential; Regional cluster support.	High agricultural potential; Emerging university-local economy links; EU integration benefits.
Weaknesses	Innovation gap in rural areas; Brain drain; Low private R&D investment.	Centralized governance; Low institutional trust; Uneven rural infrastructure.	Weak rural innovation systems; Institutional fragmentation; Skills mismatch.
Opportunities	Smart specialization strategies; Digital agriculture; Green economy initiatives.	Rural entrepreneurship support; Diaspora engagement; Tourism innovation.	Digital rural hubs; Value-added agriculture; Public-private partnerships.
Threats	Aging population; RIS coordination issues; Dependence on EU funds.	Political influence on RIS; Youth unemployment; Climate risks.	Rural poverty; Migration trends; Corruption and weak governance.

Source: Own research.

In summary, on the role of RIS in supporting decent job creation and economic growth (SDG 8) in rural areas of Poland, Hungary and Romania. **Poland** has made extensive use of EU structural and cohesion funds, which have positively impacted rural region development. (Tiţa, Bătuşaru et al., 2015; Popescu, 2015). A key strength is the decentralised governance structure and a strong agricultural base that can be supported by agri-tech innovation. However, significant challenges remain, such as the innovation gap between urban and rural areas and the brain drain (Keene et al., 2024). Despite these obstacles, there are significant development opportunities through smart specialisation strategies, digital agriculture, and the green transition (Fragomeli et al., 2024). In the long term, risks include an ageing rural population and potential reductions in EU funding (Ahlmeyer, Volgmann, 2023). **Hungary** has a well-established formal RIS framework, but its practical implementation is hindered by centralised governance

and low trust among local stakeholders. The performance results of the companies in Hungary's food industry are largely shaped by regional location, sectoral characteristics, as well as the size and age of the companies (Nagy et al., 2025). In Hungary indicate three distinct types of regional innovation systems based on knowledge function synergy: Budapest functioning as an agglomeration economy; the north-western regions integrated into the European Union; and the southern and eastern regions, where central planning and public R&D continue to play a dominant role in shaping innovation system dynamics (Lengyel, Leydesdorff, 2011). **Romania** has substantial agricultural potential and vast rural areas, but their integration into innovation systems remains weak also Romanian labor productivity level is lower than that achieved in agricultural performance in the European Union (Teodor, 2015). The reduction of disparities between urban and rural areas in Romania is possible through government policies that support private investment, infrastructure development, and better use of resources in education and healthcare, which will allow agriculture to fully realise its potential (Mihai-Valentin-Cătălin, Elian-Gabriel, 2024). Romania could benefit from the development of digital rural centres, investments in value-added agriculture and public–private partnerships (Dumitru et al., 2021). However, persistent poverty and corruption (Timu, Vilcu, 2025), rural depopulation and lack of basic services, as well as population ageing, do not support the economic sustainability growth in Romanian agriculture (Vlad et al., 2024; Marioara, Armanca, 2019). In conclusion, Regional Innovation Systems in Poland, Hungary and Romania have the potential to drive decent job creation and economic growth in rural areas. However, their impact is highly shaped by national governance structures, institutional capacity, and the effective integration of local innovation with agri-tech and regional development strategies.

How and to what extent do RIS facilitate the development of infrastructure, innovation, and industry (SDG 9) in peripheral rural areas?

RIS play an increasingly central role in advancing SDG 9 — which focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation — especially in peripheral rural areas of Poland, Hungary, and Romania. These areas face distinct structural disadvantages, such as poor connectivity, limited institutional capacity, and weak presence of the private sector. However, RIS oriented policies and EU cohesion strategies have begun to reverse some of these trends. Here is a breakdown of how and to what extent RIS are facilitating development (tab. 6).

Table 6.
Sustainable Development Goal 9 - facilitate the development of infrastructure, innovation, and industry (SWOT Analysis)

SWOT Dimension	Poland	Hungary	Romania
Strengths	Strong alignment of RIS with regional development strategies; effective use of EU funds; growing innovation hubs in some rural regions.	Formal RIS framework and existing clusters; some success in food/agro-industrial sectors; national support for industrial parks.	EU support frameworks available; initial steps toward rural digital hubs; strong agricultural base for industry development.
Weaknesses	Persistent urban-rural infrastructure gap; limited private sector participation in rural innovation; uneven digital access.	Over-centralisation limits responsiveness to rural needs; low trust among actors; insufficient local innovation absorption.	Fragmented RIS structure; poor infrastructure and institutional capacity in rural peripheries; weak innovation networks.
Opportunities	Expansion of broadband and smart specialisation strategies; potential to develop agri-tech clusters in peripheral regions.	EU and national support for regional cluster expansion; rural tourism and bioeconomy sectors offer industrial potential.	Development of renewable energy and agro-industrial zones; digital transition could bridge rural divide.
Threats	Dependence on external funding; demographic decline in rural areas; risk of innovation concentration in urban cores.	Political interference; weak regional institutions; rural infrastructure lag impedes industrial diversification.	Corruption and governance issues; outmigration; limited scalability of pilot initiatives in rural zones.

Source: Own research.

Poland has achieved notable progress in aligning Research and Innovation Strategies for Smart Specialisation (RIS3) with rural development, particularly in its eastern regions such as Podkarpackie, Lubelskie, and Świętokrzyskie. Once peripheral, these areas are increasingly integrated into broader innovation networks through EU and national policies. Infrastructure investments—particularly in transportation through the Via Carpathia corridor and broadband access—have improved with support from EU Cohesion and ERDF funds, although rural digital gaps persist (Adamowicz, 2021; Bădîrcea et al., 2025). RIS3 in Poland has spurred innovation clusters in agri-tech, smart energy, and bioeconomy, with grassroots engagement facilitated by Local Action Groups (LAGs) and innovation hubs. In contrast, **Hungary's** RIS3 landscape reflects centralised governance, with Budapest shaping much of the innovation agenda. Peripheral regions such as Szabolcs-Szatmár-Bereg and Baranya often remain disconnected from the country's innovation sector, facing inadequate transport and broadband infrastructure (Surówka at al., 2021). Here's a polished academic-style paragraph (acapit) based on your draft.

Although Hungary's Smart Specialisation Strategies (S3) place strong emphasis on information and communication technologies (ICT) and the green economy—reflecting the concept of fostering innovation through strategic investment (Kopczynska, Ferreira, 2020) — the benefits are unevenly distributed across the country. Rural regions in particular gain less from these initiatives due to the absence of local innovation brokers and technology transfer offices (Meyer et al., 2022). In addition, industrial modernisation beyond major urban centres remains constrained by weak university–industry links and the limited availability of venture

capital. As Korniyenko (Korniyenko, 2024) highlights, Hungary's rural development potential will remain underutilized unless more decentralized support mechanisms are established. **Romania** presents a more fragmented picture. Regions like Teleorman, Vaslui, and Olt suffer from chronic underdevelopment, institutional inefficiencies, and limited absorptive capacity. Despite formal RIS3 structures, their implementation varies drastically by region, often reflecting local administrative strength or weakness (Ionescu et al., 2023; Claudia, Mihaela, 2022). EU-backed infrastructure projects have improved road and digital access in some areas, but long-term sustainability remains a concern. Innovation in agriculture and renewable energy shows promise, especially in cities such as Cluj and Timișoara, yet most rural industries still depend on traditional sectors of low-productivity (Zamborsky, 2023). In addition, institutional fragmentation and inconsistent regional strategies continue to obstruct the implementation of cohesive innovation policy (Kruse et al., 2023). Across these countries, a common pattern emerges: S3 have opened important opportunities for rural development, but success hinges on local capacity, infrastructure, and governance decentralisation. As such, while Poland shows signs of meaningful RIS3 integration, Hungary and Romania struggle with institutional and geographic asymmetries that dilute the impact of innovation-driven policies.

What forms of RIS support enable the implementation of sustainable and "smart" rural community development strategies (SDG 11)?

The development of sustainable and "smart" rural communities under SDG 11 — which emphasizes inclusive, safe, resilient, and sustainable settlements — in Poland, Hungary, and Romania is increasingly supported by RIS. These systems provide a range of enabling mechanisms that link local governance, innovation actors, and EU structural funding to foster localized smart development in rural regions. Detailed review of how RIS support manifests in each country (tab. 7).

Table 7.
SWOT Analysis of RIS Support for SDG 11 in Poland, Hungary, and Romania

SWOT Category	Poland	Hungary	Romania
Strengths	Decentralized RIS supports regional adaptation. Active grassroots projects via LAGs. Strong local university collaboration.	Centralized RIS gives strategic direction. Digital hubs play a role in supporting pilot projects in rural areas. One example of success is the use of Internet of Things (IoT) technologies in agriculture.	Alignment of RIS with Smart Villages. EU-funded pilots in energy and e-gov.
Weaknesses	Regional fragmentation in RIS execution. Heavy reliance on EU funding. Tech disparity in remote areas.	Limited rural academic capacity. Urban bias in RIS resource distribution. Low local autonomy in planning.	RIS implementation is nascent. Fragmented governance, low capacity. Weak rural innovation infrastructure.

Cont. table 7.

Opportunities	Scale successful S3 pilots nationally. Deepen municipal-university synergies. Expand RIS into climate adaptation.	Decentralize elements of RIS for rural fit. EU/Horizon funding for rural gaps. Engage NGOs and rural SMEs.	Leverage Smart Villages to scale RIS. Boost digital inclusion via EU funding. Enhance RIS via university networks.
Threats	Uneven regional outcomes due to autonomy. Political shifts affecting decentralization. Overlapping projects from weak coordination.	RIS centralism may limit rural innovation. Funding risk from EU governance concerns. Institutional resistance to change.	Low fund absorption could stall projects. Rural depopulation threatens scale. Institutional inertia and low innovation culture.

Source: Own research.

Poland's decentralised RIS model enables rural regions to customise their (S3) based on local potential. Regions like Lubelskie and Podkarpackie emphasise sustainable agriculture, renewable energy, and digital services (Adamowicz, 2021). Through EU funds like the Rural Development Programme (RDP) — *is a policy and funding framework primarily designed by the European Union to promote sustainable development in rural areas. It aims to enhance the competitiveness of agriculture, ensure sustainable management of natural resources, and support inclusive growth and quality of life in rural regions* (Czyżewski et al., 2018), these areas have introduced living labs, smart mobility services, and renewable microgrids (Wieliczko et al., 2021). RIS support has also enabled Local Action Groups (LAGs) — *these groups bring together local stakeholders; such as residents, businesses, NGOs, and local authorities to foster sustainable rural development, social cohesion, and economic diversification through bottom-up approaches* (Gargano, 2021) — to initiate participatory projects such as digital public platforms, smart irrigation, and green building. These projects are especially active in Małopolska and Świętokrzyskie, where RIS interacts with municipal planning and local universities (Surówka et al., 2021). This regional and bottom-up alignment reflects how Poland's RIS fosters sustainable innovation at the grassroots level.

Hungary centralised RIS meets rural fragmentation. Hungary's RIS structure is notably centralised, with national ministries and Budapest-based agencies controlling much of innovation funding and strategic direction. This top-down approach results in an unequal distribution of innovation support, often favouring urban or capital regions. Peripheral counties experience weak integration into RIS governance due to underdeveloped infrastructure and institutional isolation. Although Hungary's S3 framework emphasises digital technologies and green economy transitions, few rural areas have benefited meaningfully. The implementation of EU funding and Smart Specialisation Strategies (S3) is frequently channeled through sectoral calls that lack sufficient territorial differentiation. This approach often overlooks the specific innovation ecosystems of peripheral regions, where the absence of localized innovation intermediaries—such as innovation brokers or technology transfer hubs—significantly constrains the effective deployment and regional impact of RIS3. Industrial development is similarly skewed, with rural industrial zones underutilized and lacking links to universities or

venture capital ecosystems. RIS implementation remains fragmented due to minimal rural stakeholder engagement and limited absorptive capacity at the municipal level. **Romania's** rural peripheries—such as Teleorman, Vaslui, and Olt—are among the most underdeveloped in the EU, facing deep-rooted structural challenges. Although RIS have been introduced across regions, their implementation suffers from fragmentation and low institutional capacity at the local level. Infrastructure gaps remain severe: many communes lack quality roads and digital connectivity. Although EU investments have expanded access, concerns about long-term sustainability and governance remain. Innovation outcomes are uneven across regions. Although Timișoara and Cluj have developed robust innovation ecosystems—including smart agriculture, digital services, and green energy integration—other rural areas struggle with low absorptive capacity and a lack of RIS-aligned support structures. Regional Development Agencies (RDAs) — *are publicly funded institutions tasked with promoting economic development and regeneration in specific geographic areas* (Danson et al., 1998) — the main intermediaries for RIS in Romania, have limited staff and insufficient budget autonomy. Industrial modernization remains confined to urban pilot zones, with most rural economies still relying on low-productivity agriculture or extractive sectors.

Academic actors engage with the components of RIS through diverse and multilayered interactions that critically shape the performance of regional innovation processes and the implementation of S3, particularly in rural or less-developed regions. In decentralised systems such as Poland, universities and research institutes often collaborate directly with local governments, businesses, and civil society through platforms, e.g. LAGs. These actors contribute by co-developing applied research, facilitating technology transfer, and training local talent aligned with regional S3 priorities (e.g., renewable energy or sustainable agriculture). Conversely, in centralised systems like Hungary, academic actors often have fewer institutional linkages with rural RIS components (Lengyel, Leydesdorff, 2011b; Zsibók, 2011) due to the concentration of innovation governance in Budapest. This leads to underdeveloped triple helix interactions between universities, industry, and government actors in peripheral regions, where universities are underfunded and less engaged in regional development. In Romania, while academic actors in urban hubs (like Cluj and Timișoara) are deeply embedded in innovation ecosystems. Rural universities serve as pivotal regional anchors for knowledge dissemination, innovation, and community engagement, positioning them as strategic actors within place-based development and territorial cohesion frameworks (Ciocan et al., 2024). In general, the degree of academic interaction with the RIS components is shaped by governance models, funding mechanisms, and the presence (or absence) of collaborative infrastructures at the regional level.

In what ways do RIS promote responsible consumption and production (SDG 12) by supporting technological, social, and organizational innovations at the local level?

In recent years, RIS have emerged as critical instruments for embedding sustainable development principles into regional policy and practice throughout the European Union. As the urgency to achieve the SDG intensifies—particularly SDG 12, which emphasises responsible consumption and production—countries are increasingly using RIS as platforms for eco-innovation, social engagement, and governance reform. This comparative analysis examines how three Central and Eastern European countries—Poland, Hungary, and Romania—are operationalising RIS to support sustainability transformations. Despite differing political and economic contexts, all three countries demonstrate growing alignment between innovation ecosystems and sustainable development agendas (tab. 8). Through technological innovation, social participation, and organisational restructuring, these RIS models reveal diverse but converging pathways toward systemic change. Drawing on recent scholarship and policy developments, this overview highlights how RIS can serve as a facilitator of regional resilience and long-term ecological transition.

Table 8.
RIS from consumption and production (SDG 12) perspective

SWOT	Poland	Hungary	Romania
Strengths	Strong EU policy alignment; eco-innovation clusters; smart governance.	Municipal-driven RIS; circular economy focus; digital public services.	University- ties; smart specialization; RIS consortia with SMEs.
Weaknesses	Dependence on EU funding; regional disparities; uneven innovation uptake.	Financial limits; political instability; regional implementation variance.	Innovation lag; fragmented governance; low public sustainability awareness.
Opportunities	Expand green tech partnerships; scale co-creation; boost specialization.	Strengthen local RIS resilience; increase EU funding use; enhance community projects.	Grow circular economy; expand SDG education; use RIS for regional development.
Threats	Bureaucratic inertia; EU funding risks; digital/green skills gap.	Overreliance on local governance; low R&D investment; economic volatility.	Policy discontinuity; limited innovation capital; urban-rural RIS divide.

Source: Own research.

Each country—Poland, Hungary, and Romania—explaining how their RIS support SDG 12: Responsible Consumption and Production through technological, social, and organisational innovations: **Poland's** RIS demonstrate a growing alignment with sustainable development, particularly in fostering responsible consumption and production. At the technological level, Poland has developed eco-innovation clusters focused on green manufacturing, digitalisation of industry, and environmental technologies. Social innovations are implemented through Responsible Research and Innovation (RRI), — *is a process that ensures science and innovation are conducted ethically, transparently and in the public interest, recognising their potential risks, uncertainties and social impacts* (Burget et al., 2017) — frameworks that involve local communities in co-creation activities, especially within

regional labs and smart specialisation sectors. Organizationally, Polish municipalities are increasingly adopting "smart governance" models that integrate sustainability metrics into public procurement and local development plans. According to (Weresa, Kowalski, 2022), these shifts are aided by EU cohesion policies and strategic funding mechanisms that enable RIS to function as platforms for eco-conscious transformation. The convergence of public institutions, universities, and enterprises facilitates a coordinated push toward SDG 12. **Hungary's** RIS model integrates sustainability primarily through its decentralised governance and municipal engagement strategies. Technologically, Hungary has focused on improving resource efficiency, particularly through the integration of renewable energy systems and waste-reduction technologies at the municipal level. Socially, local governments are vital actors, using participatory mechanisms to co-develop sustainable practices such as localised circular economy initiatives and awareness campaigns on consumption behaviour. Organizational innovations in Hungary include the digital transformation of public services and the integration of SDG-aligned KPIs in local policy frameworks. Study (Nagy et al., 2018) emphasize that while financial constraints exist, many Hungarian cities have pioneered the use of RIS tools to embed sustainability into innovation policy. These tools help buffer against central political volatility by reinforcing bottom-up resilience in rural and urban municipalities. In addition, RIS-driven local strategies increasingly leverage EU programmes and sustainability indicators to align with SDG targets in areas like energy efficiency and public infrastructure (Brodny, Tutak, 2023). In **Romania**, RIS structures are increasingly geared towards enabling sustainable production and consumption through a combination of technological, social, and organisational advancements. Technologically, regional innovation is being directed towards supporting circular economy models, energy-efficient technologies, and low-waste production systems. Social innovation is evident in the promotion of community-university partnerships, where SDG literacy and participatory design are embedded in local projects and university curricula. Organisationally, Romania's RIS efforts are moving toward a more integrated governance model that links regional development agencies, academic institutions, and SMEs in sustainability-orientated consortiums. (Puiu, 2024) notes that although Romania still lags behind EU frontrunners, significant progress is being made through RIS-supported smart specialization strategies, which target local ecological and economic strengths for systemic innovation in support of SDG 12 (Suciu, Năsulea, 2019).

How do the strategies and effectiveness of RIS vary across selected Central and Eastern European countries (e.g., Poland, Romania, Hungary) in supporting SDG implementation in rural areas?

This SWOT analysis compares the strategies and effectiveness of RIS in supporting the SDGs in rural areas in three Central and Eastern European countries: Poland, Romania, and Hungary (tab. 9). The analysis identifies the strengths, weaknesses, opportunities, and threats each country faces in this context.

Table 9.
SWOT Analysis of RIS Strategies for SDG Implementation in Rural Areas

SWOT Category	Poland	Romania	Hungary
Strengths	Strong institutional frameworks for RIS. Effective use of EU funding. Advancing rural digitalization	RIS aligned with EU RIS3. Strong agricultural base. Growing IT sector supports smart rural initiatives.	Integration of RIS with national SDG goals. Rural innovation clusters and incubators. Agricultural innovation tradition.
Weaknesses	Limited rural governance capacity. Urban-biased RIS design. Low innovation uptake in rural SMEs.	Weak coordination across institutions. Poor RIS impact monitoring in rural areas. Infrastructure gaps in rural zones.	Centralized, top-down RIS planning. Limited attention to social SDGs. Political influence over regional decisions.
Opportunities	Agri-tech and bioeconomy development. EU Green Deal alignment. Public-private partnerships.	EU structural funds for capacity building. Smart villages and digital inclusion. Renewable energy in rural regions.	Cross-border rural innovation. Cultural and eco-tourism potential. Horizon Europe rural programs.
Threats	Youth outmigration. Centralization weakening local strategies. Dependence on EU funding.	Persistent rural poverty. Administrative fragmentation. Agricultural vulnerability to climate change	Democratic backsliding. Urban-rural digital divide. Regulatory and policy unpredictability.

Source: Own research.

Poland stands out for its strong institutional support for implementing RIS and effective use of EU funds, which fosters digital transformation in rural areas. However, the adoption of rural innovation is hindered by weak local governance capacity and urban-centric RIS design (Adamowicz, Zwolińska-Ligaj, 2020; Widomski, Musz-Pomorska, 2023). Demographic challenges like youth outmigration and dependency on EU funding present significant threats to sustainability. **Romania** shows strong alignment between RIS and SDG targets and has a strong agricultural base. However, the lack of coordination among institutions and administrative fragmentation weaken the effectiveness of rural RIS (Firoiu et al., 2019); (Bădîrcea et al., 2025). While benefiting from EU structural funds for digital infrastructure and renewable energy in rural areas, the country continues to face high rural poverty rates. However, Romania has strategic potential to advance smart villages and integrate renewable energy solutions into rural development (Mihai, Iatu, 2020). **Hungarian** RIS strategies are characterised by a centralised top-down approach, which limits the engagement of local stakeholders. Despite a strong tradition in agricultural innovation and existing rural clusters, Hungary faces serious challenges related to digital divides and regulatory instability (Nagy et al., 2018). However, the country has significant potential in cross-border cooperation, cultural tourism, and the use of EU programmes like Horizon Europe. However, political centralization and democratic backsliding pose critical threats to regional innovation governance (Gica et al., 2021).

What are the key barriers and enablers for effectively aligning RIS activities with the SDG agenda in agriculturally oriented regions?

To better understand the dynamics of aligning Research and Innovation Strategies (RIS) with Sustainable Development Goals (SDGs) in agriculturally orientated regions, table 10 presents a SWOT analysis identifying the key strengths, weaknesses, opportunities and threats that act as enablers or barriers to effective integration.

Table 10.
SWOT Table: RIS & SDG Alignment in Agriculturally Oriented Regions

SWOT Category	Poland	Romania	Hungary
Strengths	- Strong RIS institutions. - Efficient EU fund absorption. - Agri-tech and bioeconomy support.	- Large agricultural base. - SDG alignment in national plans. - Access to EU rural funds.	- Agricultural innovation clusters. - Tradition in rural R&D. - Sectoral RIS-SDG integration.
Weaknesses	- Urban-biased RIS focus. - Weak rural governance. - Low innovation in small farms.	- Institutional fragmentation. - Poor rural RIS monitoring. - Rural infrastructure deficits.	- Top-down planning. - Limited social SDG focus. - Weak stakeholder inclusion.
Opportunities	- Green Deal alignment. - Smart village development. - Digital agriculture expansion.	- Renewable energy in rural zones. - Smart village pilots. - EU funds for inclusion.	- Cross-border RIS initiatives. - Sustainable tourism. - Horizon Europe rural innovation grants.
Threats	- Youth outmigration. - Dependence on EU funds. - Regulatory implementation delays.	- Persistent rural poverty. - Climate-related agri risks. - Administrative inefficiencies.	- Democratic backsliding. - Digital rural-urban divide.- Unpredictable policy environment.

Source: Own research.

Poland has a well-developed institutional structure for RIS and effectively absorbs EU funds to support digital transformation and innovation in rural areas. Initiatives such as smart villages and the development of the bioeconomy are gaining momentum, and the country is making progress in implementing RIS3 strategies aligned with the Green Deal priorities. Strengths also include expanding digital infrastructure and the potential for public–private partnerships (Adamowicz, Zwolińska-Ligaj, 2020; Raszkowski, Bartniczak, 2019). Despite these advances, Poland faces major barriers, including limited local governance capacity, low innovation acceptance in rural SMEs, and an urban-biassed approach to policy design. Youth outmigration from rural areas weakens the capacity of the local community to implement the SDGs. Additionally, the lack of long-tethe caserm monitoring of RIS impact on sustainable development complicates effective alignment (Adamowicz, Zwolińska-Ligaj, 2020; Chmieliński, Gospodarowicz, 2018): Romania demonstrates strong alignment between national development plans and the Sustainable Development Goals, leading to increased use of EU structural funds to modernise rural infrastructure and renewable energy. Rural areas, rich in agricultural resources, are key beneficiaries of smart village projects supported by RIS policies (Firoiu et al., 2019; Mihai, Iatu, 2020). Efforts are also underway to strengthen digitalization and social inclusion in rural zones.

On the other hand, **Romania** continues to struggle with serious barriers: administrative fragmentation, poor institutional coordination, and a lack of effective monitoring systems for the impact of RIS on the SDGs. High rural poverty and limited innovation capacity between local farms are critical challenges to sustainable development. Climate-related issues, such as droughts and unstable crop yields, further hinder efforts to adapt RIS to the SDG framework (Bădîrcea et al., 2025). **Hungary** has a strong tradition of agricultural innovation and well-functioning rural clusters, some of which integrate the SDG goals with the RIS policy. Support from EU programmes such as Horizon Europe opens opportunities for cross-border projects and sustainable tourism development in rural regions. The country also employs digital tools in agriculture, especially for precision agriculture and resource efficiency (Brodny, Tutak, 2023). However, Hungary's RIS system remains highly centralised with low stakeholder participation at the local level. There is also a limited focus on social SDGs such as equality and education. Institutional backsliding and political instability create regulatory uncertainty and weaken long-term strategic planning. Significant digital divides between urban and rural areas also constrain the transformative potential of RIS (Gica et al., 2021; Nagy et al., 2018).

4. Summary

Regional Innovation Systems in Poland, Romania, and Hungary play an increasingly important role in supporting the implementation of Sustainable Development Goals (SDGs), particularly in agricultural and peripheral rural areas. A comparative analysis shows that while all three countries rely on similar EU policy tools, the effectiveness of their implementation and local adaptation vary significantly. **Poland** stands out with well-developed RIS institutions, effective absorption of EU funds, and a strong research and advisory base in the agricultural sector. Thanks to its decentralised governance model, many regions, especially in the east, are implementing innovations in areas such as agri-tech, the bioeconomy, and green energy. Nevertheless, Poland still faces challenges including low adoption of innovation among small farms, youth outmigration from rural areas, and resource concentration in urban regions. In **Hungary**, RIS operate mainly under a centralised model, where strategic decisions and financial resources are concentrated in Budapest. Although the country has a tradition of agricultural innovation and active local clusters, limited regional autonomy, weak institutional integration, and low innovation absorption significantly weaken the impact of RIS on local development. **Romania**, on the other hand, has significant agricultural potential and a growing IT sector, but suffers from poor coordination among institutions, fragmented implementation of RIS, and lack of local capacity. Projects like smart villages and investments in digital and renewable energy infrastructure show promising directions, but their effectiveness depends on improved implementation capacity.

All three countries face similar challenges: outmigration of youth from rural areas, dependence on EU funding, lack of long-term RIS impact monitoring, and limited participation of local communities in innovation processes**.** At the same time, development opportunities lie in the implementation of the European Green Deal, the advancement of the circular economy, the digitalisation of agriculture, and the strengthening of cooperation between universities, municipalities and the private sector. However, effective alignment of RIS with the SDG agenda requires, above all, decentralisation of governance, strengthening institutional capacity at the local level, and embedding innovation in the real needs of rural communities.

In all cases, the successful implementation of the SDG is based on decentralised governance, inclusive stakeholder engagement, and long-term sustainability planning within RIS frameworks.

5. Conclusion and recommendation

Common challenges in all three countries include the migration of young people from rural areas, a strong dependence on EU funding, the lack of long-term monitoring of RIS impacts, and the limited participation of local communities in innovation processes. At the same time, all three countries have opportunities to strengthen their systems by making fuller use of the possibilities offered by the European Green Deal—particularly in the fields of circular economy, renewable energy and digitalisation of agriculture.

In **Poland**, the priority should be to support small farms in adopting agricultural technologies and sustainable practices, while also fostering entrepreneurship and developing digital infrastructure in rural areas to counteract youth outmigration. It is equally important to direct RIS funding more strategically toward peripheral regions and to strengthen long-term monitoring of how these initiatives contribute to the Sustainable Development Goals. In **Hungary**, the key task is to decentralise RIS governance by granting more competences and resources to regions. Closer cooperation between universities, clusters and local development institutions is also necessary, in addition to creating conditions for greater innovation absorption through advisory services and pilot projects. Increasing the participation of municipalities and local communities in decision-making processes is vital to reduce the dominance of the top-down model. In **Romania**, policy should focus on improving coordination between national and regional levels and building the administrative capacity of local governments, particularly in implementing smart village concepts, digitalisation, and renewable energy projects. Rural innovation ecosystems also require support, which can be achieved through stronger cooperation between universities, municipalities, and the private sector. A further priority is to ensure easier and more transparent access to EU funds for SMEs and local communities.

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THE SERVITIZATION BUSINESS MODEL AS A KEY TO SUCCESS FOR MODERN COMPANIES

Adam WIŚNIEWSKI

University of Warmia and Mazury in Olsztyn; adam.wisniewski@uwm.edu.pl, ORCID: 0000-0003-0395-9308

Purpose: The purpose of this study was to identify the premises and organizational predispositions for the implementation of servitization in a manufacturing enterprise. The study seeks to explore how servitization, as an evolutionary change in business models, contributes to long-term competitiveness and value creation int the context of digital transformation and shifting customer expectations.
Design/methodology/approach: The research follows a qualitative case study approach using a semi-structured individual interview with a decision-maker in a medium-sized furniture manufacturing company located in the Warmian-Masurian Voivodeship in Poland. The company was purposefully selected due to its interest in extending its offering with service components. The interview tool was developed based on a literature review on servitization and business models, and organized int six thematic blocks. The study allows for a detailed analysis of organizational context, motivations, resources and technological readiness.
Findings: The study shows that the company exhibits both internal readiness (basic service infrastructure, openness to innovation, partial service implementation) and external drivers (market expectations, competitive pressure) for adopting a servitization model. Nevertheless, significant barriers such as skill shortages, limited IT integration and cultural resistance persist. The findings highlight the necessity of a gradual, pilot-based implementation strategy and underscore the potential of digital servitization in combining digitalization and service orientation.
Research limitations/implications: Due to the exploratory and single-case nature of the study, the results cannot be generalized to all manufacturing enterprises. The analysis reflects the subjective view of one responded and represents a pre-implementation phase. Future research should include multiple case studies, longitudinal data and customer perspectives to deepen understanding of servitization dynamics across industries.
Practical implications: The study offers insights for manufacturing companies considering servitization by outlining the key organizational capabilities required for successful implementation. It provides a roadmap for aligning resources, modifying organizational culture and integrating digital tools to build service-based competitive advantage. The results suggest that service bundling and long-term customer relationships can enhance financial stability and operational efficiency.
Social implications: Servitization supports broader sustainability and circular economy goals by shifting the focus from product sales to lifecycle management and value co-creation. This approach aligns with environmental policies and promotes responsible consumption.

It also redefines the customer's role as a co-creator, fostering deeper engagement and personalized experiences.
Originality/value: The paper contributes to the growing body of research on servitization by providing an in-depth, contextualized understanding of its prerequisites and challenges from an organizational perspective. It emphasizes the complementary relationship between servitization and digitalization and offers practical and theoretical insights into business model innovation in manufacturing.
Keywords: servitization, business model, manufacturing firms.
Category of the paper: Research paper.

1. Introduction

Classically understood production activity is no longer sufficient for some sectors. Consumption and the all-pervasive trend of consumerism are the subject of research by representatives of many scientific disciplines - economics, management, sociology, etc. This trend left a particularly significant mark about enterprises at the beginning of the 21st century with the increase in access to information and the ease of its assimilation (Rydzak, 2023). A second factor related to the issue at hand is also globalization. This is a phenomenon that is understood differently in different areas of economic life. From an economic point of view, it is defined as processes of integration of world markets for goods and services, labor and capital (Tomkiewicz, 2023). Consequently, they can lead to a situation of market saturation, significantly affecting the specifics of the operation of manufacturing (Kim, 2011) and service companies (Bleischwitz et al., 2018).

Today's business environment is characterized by the growing importance of digital technologies and the need to adapt operating modes, strategies and business models to changing customer needs and expectations. Within the processes taking place, the trends of digitalization and servitization can be distinguished. Although the two concepts are often co-occurring, their nature differs significantly, and they present different approaches to business development. Digitalization is the process of using digital technologies to transform operations, products, services and business models (Brennen, Kreiss, 2016). Its warp is, in addition to the automation of existing processes, primarily the creation of new value through data analysis, the development of digital platforms and the use of artificial intelligence. A team of researchers led by Verhoef (2021) noted that digitalization has enabled the emergence of new business models such as subscription, sharing economy or platform models.

In turn, the essence of servitization can be described as the transformation of the traditional product sales model into a model based on offering end-to-end solutions that combine products and services (Baines et al., 2009). A manifestation of this can be, for example, the implementation of technical consulting, maintenance, fleet management or training services aimed at increasing customer loyalty and ensuring a stable revenue flow (Raddats et al., 2016).

Companies that apply servitization acquire several benefits, such as differentiating themselves from their competitors, building long-term customer relationships or increasing margins through more value-added services. The issue of servitization will be discussed comprehensively later in this article.

2. Literature review

These business models are an important area of research, the precise explanation of which promotes sound organizational decision-making and long-term performance. The essence of a business model is to explain how an organization creates, delivers and captures value. A business model constructs a set of logical relationships between key components such as the value proposition, customer segments, distribution channels, customer relationships, revenue streams, key resources and activities, and key partners and cost structure (Osterwalder, Pigneur, 2010). It can also be understood as 'the design or architecture of how a business delivers value to customers, attracts customers and converts payments into profit (Teece, 2010). What may be a key point from the point of view of the topic at hand, the concept of the business model has become increasingly important from an innovation perspective, as it enables the creation of competitive advantage not only at the product level but also in the way it is delivered (Chesbrough, 2007). Business model innovations can anticipate changes in the orphan, acting as a tool for adaptation and differentiation of the company (Gassmann, Frankenberger, Csik, 2014). In a systems perspective, the business model can be understood as a mechanism that integrates different areas of an organization's activities, enabling it to market itself coherently and effectively (Morris, Schindehutte, Allen, 2005). One of the most popular approaches to visualizing a business model is the business model canvas (Osterwalder, Pigneur, 2010), which has gained importance especially in the practical aspects of companies.

A characteristic feature of the business model is also its dynamic nature. It is not fixed 'forever' but is subject to change under the influence of both internal (e.g. digital transformation, changes in company policy) and external (for example, regulatory or technological) factors. An effective business model should be flexible and able to evolve in response to a changing environment (Wirtz, 2011). Increasingly, the business model is also seen as an element that determines the sustainable development of an organization. Hence the frequent emphasis on the terms 'sustainable business model' or 'circular business model', which emphasize the need to consider social and environmental goals alongside economic objectives (Geissdoerfer, Vladimirova, Evans, 2018).

The literature emphasizes that digitalization and servitization are not identical or exclusive phenomena. However, they can be mutually supportive. This can be the case, for example, in so-called digital servitization, the premise of which is the use of digital tools to design,

implement and monitor services accompanying physical products (Kohtamäki et al., 2019). In practice, this means, for example, using IoT technologies to remotely monitor the condition of equipment and predictive analytics to plan maintenance before failure occurs.

Despite their complementarity, the two phenomena are fundamentally different in terms of their strategic objectives. Digitization focuses on streamlining internal operational events, reducing costs and using data as a key resource. Servitization, on the other hand, focuses on creating external value. This can take place by increasing customer satisfaction and loyalty (Gebauer et al., 2005). These perspectives imply the need for a different approach to management, employee competence and relations with the business environment. Differences can also be seen in the organizational sphere. Digitization most often requires investment in IT infrastructure, the development of digital competences and the implementation of new IT systems. Servitization, on the other hand, requires organizational change - for example, the creation of new departments responsible for the service sphere, the development of soft competences and interdisciplinary cooperation (Lenka et al., 2018). Consistently, the implementation of digitization and servitization also poses various challenges. Companies implementing digitalization face technological barriers, integration of data from different sources and digital data security issues. In contrast, organizations implementing servitization face difficulties in reformulating their offerings, training staff and winning customers over to new models of operation and value delivery (Kindström, 2010).

It may be scientifically interesting to effectively combine digitization and servitization strategies. Digitization can support servitization by creating the conditions for offering data-driven services (for example, product usage analysis, personalization of offers, remote technical support). On the other hand, servitization can provide digitalization with a business context, orienting its use towards customer needs and strictly market-based applications (Coreynen et al., 2017). The combination of these threads can also foster increased competitiveness. Companies using both solutions tend to achieve higher levels of innovation and adaptability. As has been shown, companies successfully implementing digital servitization report higher customer satisfaction, improved operational efficiency and greater financial stability (Kohtamäki et al., 2019). From a scientific perspective, the need for further research into the integration of digitalization and servitization is increasingly being advocated. The complexity and multidimensionality of these processes calls for a systems approach, cross-cutting technological, organizational, social and market factors.

When discussing the theoretical framework of the servitization model approach, the aspect of creating or shifting towards the service aspect of the business is crucial. M. Jablonski even emphasizes that servitization ‘may serve, through its ideological premise, to revolutionary and evolutionary changes in the configurations of business models, which may fit into the notion of restructuring’ (Jabłoński, 2019). What is widely considered to be the first theoretical description of the phenomenon of servitization dates to 1988, when Vandermerwe and Rada (1988) defined it as ‘the innovation of an organizations capabilities and processes to better create mutual value

through a shift from selling product to selling product-service systems. The crucial question then is at what point does service become the dominant aspect and when is it still understood as a supporting element of production? As M. Ulbrych points out, servitization occurs when services determine the course of production processes, create added value and create a competitive advantage for the industry or company (Ulbrych 2016). An extreme symptom may be a shift from a 'pure' product to a 'pure' service (Smith et al., 2014). The phenomenon of the shift to the service aspect of business is discussed by many authors. A few emerging trends can be discerned (Figure 1).

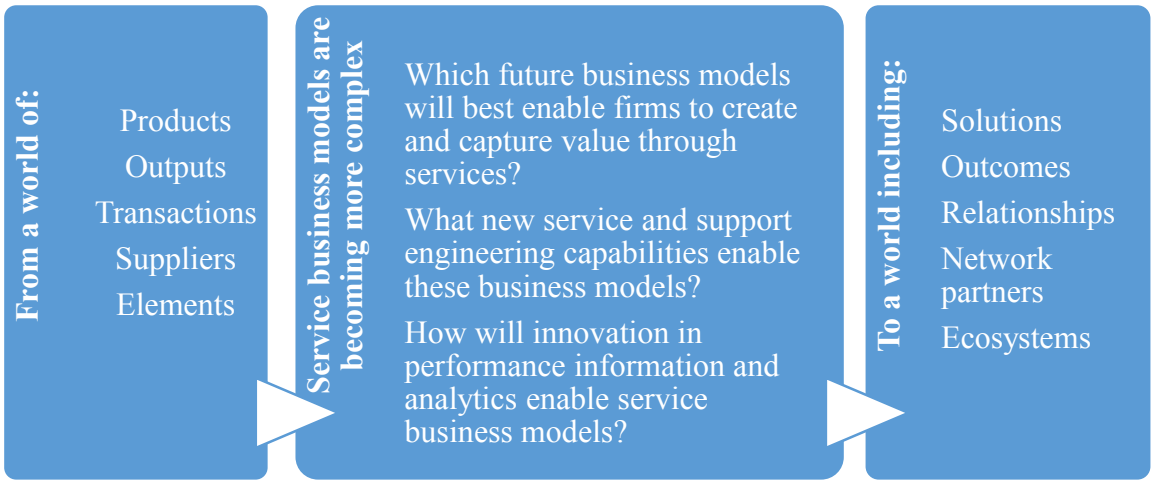


Figure 1. Describing the shift to services.

Source: Neely et al., 2011.

Moving from the 'world' of: (1) products to solutions; (2) outputs to outcomes; (3) transactions to relationships; (4) suppliers to network partners and (5) elements to ecosystems. As the authors point out, this transition does not mean the elimination of the original elements, but the addition of elements to the business that extend the functioning of the enterprises (Neely et al., 2011).

The success of servitization depends on how the advantage in resources is exploited, which influences the achievement of competitive advantage (Madhavaram, Hunt, 2008). At the same time, M. Matusek (2016) citing a study by D. Kindström and C. Kowalkowski notes that since companies may not actually be the rightful owners of all necessary resources, an approach from the resource theory side of the business 'is not entirely appropriate for understanding the servitization process of goods producers (Kindström, Kowalkowski, 2014). It therefore seems interesting to identify the determinants of the transition to a servitization business model. M. Jablonski indicated globalization, mobility of production factors, decrease in transaction costs and diffusion of technological progress (Jabłoński, 2019). The author also identified social factors as an important aspect of servitization, whose role is to build relational capital (a community of supporters of the proposed solution) and to simultaneously act with integrity and respect for the environment.

Another element determining the application of servitization is the existence of competitive pressures and the need to seek market advantage. Increased globalization contributes to product homogeneity, making competitive advantages based only on functional characteristics unsustainable (Porter, 1996). To differentiate themselves, companies seek new sources of value, including services, which are often more difficult to copy than physical products. Increasing competitiveness through servitization manifests itself in the construction of bundles of end-to-end solutions (so-called bundling), integrating product and service into a single package (Matthyssens, Vandenbempt, 2008).

The rationale for servitization is also changing customer expectations. The better-informed buyer is more demanding and expects 'tailor-made' solutions (Prahalad, Ramaswamy, 2004). The role of the user is also changing - from a passive consumer to an active co-creator of value. Buyers expect services tailored to their unique needs rather than standardized offerings (Gebauer et al., 2010). These expectations increase the importance of personalization, tailored services and advanced after-sales service.

From the company's point of view, an important issue is that the average life cycle of products is lengthening. Models based on rapid renewal of purchases therefore become ineffective (Neely, 2008). Service revenues can be more profitable than revenues from the sale of physical products while being less susceptible to the cyclical fluctuations of the economy (Baines, Lightfoot, 2013).

Another determinant of the application of the servitization model is regulation and public policy. Pro-environmental measures such as the European Green Deal or laws that are geared towards producer responsibility motivate producers to implement circular economy models (Ellen MacArthur Foundation, 2013). In these types of models, companies take responsibility for the recovery and recycling of their products. Servitization is a way to enable companies to meet these requirements, minimizing environmental impact and creating a reputation as a company committed to sustainability (Tukker, 2015).

The classical approach to manufacturing companies focuses its attention on the creation of the product and its buyer. In the servitization model, companies remain in a partnership relationship throughout the life of the product. What occurs is the creation of ecosystems in which different entities (producers, service providers, customers) co-create value (Adrodegari, Saccani, 2017). The creation of ecosystems enables better management of the product lifecycle, faster emergence and implementation of innovations and more efficient use of resources. Servitization is also a model that increases barriers to entry for new competitors. In its nature, an extended service offering increases relationships based on multi-year contracts, which effectively raises barriers to entry for new bidders (Visnijc et al., 2014). The emergence of an offering that complements physical products with services requires specific competences, infrastructure and a wide range of product usage data, which effectively limits the ability of new providers to enter the market quickly.

In the servitization model, some of the risk is transferred from the customer to the supplier (Ng, Nudurupati, 2010). This happens, for example, in specific types of contracts based on the supplier's actual performance rather than pre-planned activities. Indirectly, this also has the effect of changing the product life cycle. By making use of advanced diagnostics, the use of predictive methods or monitoring tools, companies can reduce product lifecycle costs and increase customer satisfaction which affects long-term profitability (Baines, Lightfoot, 2013).

A final aspect of implementing servitization is the need to modify the organizational culture. Employees need to learn the perspective of the buyer, changing their mindset from a typically transactional one to one of delivering continuous value (Kindström, Kowalkowski, 2014). This change determines the acquisition of new competences: service design, relationship management, data analysis and innovation (Ulaga, Reinartz, 2011).

3. The servitization business model – research results

The purpose of the research described in this article was to identify the rationale and organizational predisposition for implementing servitization in a manufacturing company. The study was exploratory in nature and is part of the trend of qualitative case studies, which provide an in-depth analysis of complex organizational phenomena in their practical context (Yin, 2017). The method used was an individual semi-structured interview with a decision-maker in the company under study. The selection of the subject was purposive. The selected company met the criteria of a medium-sized manufacturing entity, operating in the furniture industry in the Warmian-Masurian Voivodeship in Poland and showing interest in expanding its offer with service components. The interview was conducted in the form of a face-to-face meeting and lasted approximately 60 minutes. The research tool in the form of an interview questionnaire was constructed based on a review of the literature on servitization and business models. The questionnaire contained open-ended questions grouped into six thematic blocks: market and strategic context, motivations and impulses for service development, resources and competences, organizational culture and structure, technological and process readiness, respondent's subjective assessment.

The study was conducted with the organization’s chief operating officer as the decision-maker and with a cross-sectional knowledge of the topics discussed in the article. Due to lack of permission, the subject's data cannot be shared, and his/her description is limited to parameters ensuring anonymity. The survey consisted of 6 panels containing 3 questions each, the answers to which will be described below.

Market and strategic context

The respondent pointed to significant changes in the market environment, highlighting the increase in customer expectations in terms of seeking specific and individual offers and comprehensiveness of service. As he noted: ‘customers expect not just a product, but a complete buying experience - advice, trying on a piece of furniture, transport with delivery, installation at the indicated location and even interior design (visualization)’. Changing customer preferences are forcing modifications in the approach to the offer and customer relations. The company has already partly adapted to these requirements by introducing, for example, an online product configurator and developing electronic sales channels.

Motivations and impulses for service development

At a strategic level, the organization recognizes the need to expand its offering with a service element. ‘There have been discussions about introducing services - both in terms of building customer relationships and increasing margins’. The company is already introducing solutions such as extended warranty and on-site product assembly (folding) services, which have been positively received.

Resources and competences

In the area of available organizational resources, the company has the basic elements to support service activities (customer service department, logistics). There are noticeable gaps that would need to be filled to implement a wider range of service activities. As pointed out by the respondent, ‘We lack specialized personnel and IT tools for comprehensive after-sales services. The competences of the staff are at a high level in terms of handling traditional commercial activities, but there is a need to strengthen the so-called soft competences and those related to the service area in the zone of technical teams, which would be responsible for the correct course of service processes.

Organizational culture and structure

The company shows a moderate openness to innovation and new operating models. Strategic decisions are driven by market needs and based on data and interdepartmental consultation. ‘We are not afraid of experiments but approach them in stages - first a pilot then possible scaling up to the target scope’. The current organizational structure is optimal for current production activities, but there is a noticeable need to better integrate marketing activities with the technical department and to implement a unit dedicated to possible strictly service activities. Attitudes to change among employees are identified as mixed - managers are open-minded, while operational employees show some resistance to digitalization and a different customer role.

Technological and process readiness

Service-related processes are already partially present - the company offers on-site assembly, standard complaints handling and support for order configuration. However, 'the current CRM and ERP systems are not fully integrated into the after-sales service channels. The collection of customer data is in place, but their analysis is not implemented in a systematic way. Their use in decision-making requires redesign and further development. Communication with customers after the sale is carried out through multiple channels (telephone, email, website), but is not systematized in the form of an integrated system.

Subjective assessment of the respondent

The respondent presented the view that the company has the potential to implement wider service activities as an integral part of the business model. 'We are aware of what we have and what we lack. We need resources and a plan to apply the process'. He also identified what he considered to be the key barriers: staff constraints, lack of experience in service delivery, insufficient belief in the need for change and cultural resistance. Furthermore, he assessed the overall readiness positively, emphasizing the need for an informed decision and gradual implementation. 'A gradual transition in the form of an evolution with clear goals and some solutions'.

4. Summary and conclusions

The study conducted aimed to identify the rationale and organizational predisposition for implementing the servitization business model in manufacturing companies. The proceedings adopted the case study as a starting point for the development of further, more in-depth research in this area. Based on an individual semi-structured interview with a decision-maker - the operations director at the studied entity - it was possible to grasp the complexity of the conditions accompanying the potential transformation of the business model from product-centric to servitization.

According to the literature, servitization is a manifestation of an evolutionary change in the business model, in which the value proposition goes beyond traditional product delivery and includes personalization, service integration and the creation of lasting customer relationships, among others (Raddats et al., 2016, Baines et al., 2009). The results confirm the relevance of both external factors (market pressures, customer expectations, competitive actions) and internal factors (resources, organizational structure and culture) that influence the organization's readiness and to implement service priority. The study found that the organization recognizes the benefits of implementing service-prioritized solutions - including

the opportunity to differentiate itself from competitors, increase margins and enhance customer satisfaction. This practice fits in with the service-dominant logic approach (Vargo, Lusch, 2008), in which value is created in interaction with the user and is jointly created.

The interview results also indicated that the company has a partial infrastructure and elementary competences as well as the openness of the management to model changes. At the same time, a few barriers were identified - including a shortage of specialized service personnel, limited integration of IT systems and the need to transform organizational culture. From a practical perspective, the implementation of a servitization approach should be phased, considering testing activities, the development of staff competencies and building awareness of the value offered both within the organization and in its environment. The results indicate that a key determinant may be the ability to combine elements of digitalization with a service-oriented extension of the offer, so-called digital servitization (Kohtamäki et al., 2019). Such a solution makes it possible to respond faster and more effectively to market needs, but also to build more stable revenue streams.

In the conducted research procedure, several limitations important for the final reception of this description can be noticed. Due to the nature of the conducted study and its setting in the qualitative trend of case studies, the results cannot be generalized to the population of manufacturing enterprises in Poland. The analysis was performed on one entity, selected in a purposeful manner, which limits the possibilities of comparing and assessing other entities operating in different market or organizational conditions. Despite the use of a methodology enabling in-depth analysis, the study was based on the subjective perspective of a decision-maker in the enterprise, which may carry the risk of selectivity of the presented content and its interpretation. A certain specificity of the studied enterprise is its "raw" state, the pre-implementation stage of servitization. A challenge for further research may therefore be to examine the full cycle of implementation of this solution. Customer perspectives in relation to different stages of servitization implementation may also be valuable. In the context of further research, it is postulated to extend it to a larger number of cases, which would enable the identification of common patterns or differentiating features.

In the theoretical dimension, the study confirms the validity of further exploration of the issue of servitization model solutions integrating organizational, technological and business aspects. Servitization should not be perceived only as a one-time implementation of a service element, but as a complex process of value formation that requires the integration of many aspects of the company's functioning.

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