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INTERGENERATIONAL DIFFERENCES IN WORKFORCE FLEXIBILITY PREFERENCES: AN ANALYSIS OF GENERATION X AND GENERATION Y

Katarína HRUDKOVÁ

Abstract

The current labour market is characterised by the growing importance of workforce flexibility, while individual generations may perceive and prefer these forms of flexibility differently. The aim of this study was to analyse intergenerational differences in workforce flexibility preferences between Generation X and Generation Y and to identify the main factors associated with these preferences. The research is based on a quantitative questionnaire survey conducted on a sample of respondents from Generation X and Generation Y, with responses measured using five-point Likert scales.

The theoretically derived model was empirically tested through confirmatory factor analysis, which was used to verify the measurement structure of latent constructs representing workforce flexibility factors (motivational factors, barriers, job task preferences, working time preferences, and preferences regarding contractual forms of employment). Based on the obtained factor scores, the research hypotheses were subsequently tested using linear regression models and correlation analysis. The analyses were conducted separately for each generation.

The results confirmed that workforce flexibility preferences in both generations are primarily influenced by preferences for remote work, which show a statistically significant relationship with motivational factors, job task preferences, and working time preferences. At the same time, differences were identified in the strength of these relationships between Generation X and Generation Y, indicating distinct mechanisms in the formation of flexible work preferences across generations. Positive and statistically significant relationships were also identified among selected latent constructs, particularly between motivational factors and flexibility barriers, as well as between job task preferences and working time preferences.

The findings contribute to a deeper understanding of intergenerational differences in the area of workforce flexibility and provide practical implications for human resource management, particularly in designing flexible working conditions, job positions, and HR strategies that take generational specificities into account.

Key words:
Human resource management, workforce flexibility, intergenerational differences, Generation X, Generation Y

JEL Classification M12, M54, J24 https://doi.org/10.52665/ser20260101

INTRODUCTION

The current labour market is undergoing a significant transformation characterised by growing uncertainty, technological acceleration, and changing employee expectations towards work and employers. In this context, organisations are compelled to seek new approaches to human resource management in order to maintain competitiveness, workforce stability, and long-term performance (Gallo et al., 2023). One of the most prominent trends in recent years has been the expansion of Flexible Work Arrangements (FWA), which include flexibility in working time, workplace location, job tasks, and contractual relationships (Noermijati et al., 2025).

Following the COVID-19 pandemic, flexibility has ceased to be perceived as a premium benefit and has instead become an expected component of working conditions that fundamentally influences the psychological contract between employees and organisations (Noermijati et al., 2025; Schulz et al., 2024). Research further indicates that work flexibility has significant implications for job satisfaction, work-life balance, health, and turnover intentions across various sectors (Kozova et al., 2025; Hinge et al., 2025). Among knowledge workers, decisions regarding workplace location have become a dynamic process in which employees daily evaluate combinations of home offices, traditional offices, and alternative workspaces (Kuchenbauer & Besic, 2026).

Despite the growing importance of workforce flexibility, employees do not perceive and evaluate flexible arrangements uniformly. Generational differences may significantly influence work-related attitudes and expectations. Although prior research has examined flexible work and generational characteristics separately, fewer studies have analysed the multidimensional structure of workforce flexibility preferences and the relationships among motivational factors, perceived barriers, and specific flexibility dimensions within distinct generational cohorts.

Therefore, the aim of this study is to analyse intergenerational differences in workforce flexibility preferences between Generation X and Generation Y and to empirically verify a multidimensional measurement model of work flexibility. By examining structural relationships among flexibility drivers, barriers, and preference dimensions, this study contributes to both theoretical discussion and practical HRM applications.

LITERATURE OVERVIEW

However, flexibility preferences are not homogeneous and differ significantly depending on generational affiliation. Generation X, shaped by a period of economic change and uncertainty, places greater emphasis—compared to younger cohorts—on job stability, financial security, and predictability of working conditions (Gallo et al., 2023; Viterouli et al., 2024). For this generation, flexibility is often associated with the need to reconcile work and family responsibilities, particularly in the context of caring for children and ageing parents (Russo et al., 2025). Remote work and flexible working hours therefore represent for Generation X a practical tool for maintaining labour market participation and protecting health, rather than primarily a means of self-fulfilment (Moriarity et al., 2014; Kozova et al., 2025).

In contrast, Generation Y (millennials) approaches work with a strong emphasis on personal development, meaningful work, and technological integration. This generation is characterised by high expectations regarding feedback, learning opportunities, and career growth (Holban & Bedrule-Grigoruța, 2025; Gallo et al., 2023). For millennials, flexibility in working time and place is closely linked to their willingness to remain in an organisation and to their intrinsic motivation (Noermijati et al., 2025; Backman et al., 2025). Studies also suggest that technological orientation and a positive attitude towards digital tools increase the acceptance of hybrid and remote forms of work, particularly in knowledge-based professions (Panina et al., 2020; Lee, 2025).

The literature further indicates that flexibility preferences are shaped by a combination of individual values, organisational conditions, and the degree of alignment between employees' expectations and the actual design of work. The alignment between preferred and implemented forms of work is associated with higher satisfaction, lower burnout, and reduced turnover (Gee & Yeager, 2026). Conversely, the absence of clear boundaries in flexible arrangements may lead to the so-called flexibility paradox, characterised by overwork and difficulties in detaching from work (Russo et al., 2025; Schulz et al., 2024).

From a human resource management perspective, these findings represent a significant challenge. The effective design of flexible working arrangements requires consideration of generational differences, job roles, and the need for team interaction (Viterouli et al., 2024; Atan et al., 2026). At the same time, flexibility has become an important component of employer branding, with younger generations in particular associating flexible working conditions with technological advancement, transparency, and corporate social responsibility (Hakam et al., 2024; Holban & Bedrule-Grigoruța, 2025).

These theoretical insights provide the conceptual foundation for the development of the proposed multidimensional model of workforce flexibility examined in this study.

GOAL AND METHODOLOGY

In this study, we examined how work preferences and attitudes towards work flexibility are shaped within Generation X and Generation Y, and whether these attitudes can be captured through a coherent

model of latent constructs applicable in the field of human resource management. The research problem was not conceived merely in a descriptive manner, but rather as a verification of whether selected dimensions of work flexibility and related value orientations form a statistically supported structure and whether significant relationships exist among them, with particular attention paid to generational differences.

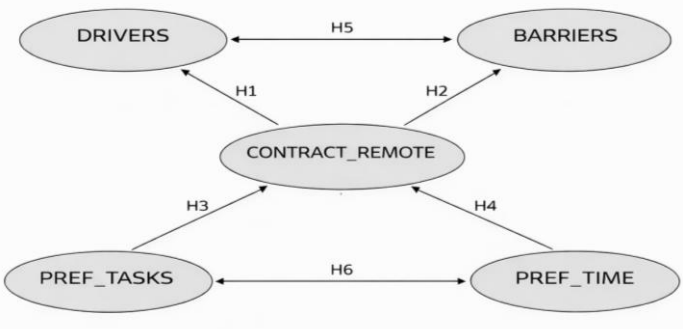
The analytical procedure consisted of two consecutive steps. In the first step, the measurement part of the model was tested using confirmatory factor analysis (CFA), with the aim of assessing whether the selected questionnaire items adequately represented the intended latent constructs. In the second step, based on the obtained factor scores, the research hypotheses were tested through regression analysis and correlation tests, conducted separately for Generation X and Generation Y. This approach enabled a comparison of the relationship structures between the two generations.

The measurement model included six latent constructs. The construct DRIVERS (motivational factors of flexibility) was operationalised through items focused on career growth, financial remuneration and benefits, family-related reasons, health and psychological well-being, technological conditions, and work-life balance. The construct BARRIERS (barriers to flexibility) included items related to lack of skills, insufficient employer support, distrust from supervisors or colleagues, and organisational or legislative constraints. Preferences regarding job content were captured by the construct PREF_TASKS, composed of items addressing job enlargement, job enrichment, and job rotation.

Time flexibility was represented by the construct PREF_TIME, which included preferences for fixed working hours, shift work, and part-time employment. Spatial flexibility and flexibility in workplace location were captured by the construct CONTRACT_REMOTE, encompassing remote work from a location other than home, home office work, and telework. Alternative forms of work arrangements were represented by the construct CONTRACT_ALT, including job sharing, flexible working hours, taking leave, and atypical working arrangements.

All items were measured on a five-point Likert scale ranging from “strongly disagree” to “strongly agree,” which led to the use of the WLSMV (DWLS) estimation method, appropriate for ordinal data. Model adequacy was evaluated using standard fit indices (CFI, TLI, RMSEA, SRMR). Data were collected through an anonymous questionnaire survey among economically active respondents via the Survio platform. A total of 437 valid responses were included in the analysis, of which 193 respondents belonged to Generation X (born 1965-1980) and 244 respondents belonged to Generation Y (born 1981-1996). Generational boundaries were defined according to widely used demographic classifications in generational and HRM research. This sample size provided sufficient statistical power to test the measurement model separately for each generation, as well as to subsequently test the formulated hypotheses and compare results between generational groups.

Figure 1: SEM model diagram



Source: Authors’ own processing

FINDINGS

In this section, we present the results of the empirical analysis in a manner that enables an objective and reliable interpretation of the relationships among the examined constructs related to work flexibility preferences. Before evaluating the relationships between latent variables and comparing generational differences, it was necessary to verify whether the proposed measurement model adequately fits the data and whether the observed indicators sufficiently represent the intended latent constructs.

Since the analysed variables are ordinal in nature and were measured using Likert scales, confirmatory factor analysis (CFA) with the WLSMV estimation method was applied to estimate the measurement model. CFA represents a fundamental step in validating the measurement structure, as it allows for the assessment of construct dimensionality and the suitability of individual indicators within each generational group.

The adequacy of the measurement model was evaluated using a set of commonly applied model fit indices, which collectively express the degree of correspondence between the empirical data and the specified model. An overview of the key fit indices for both generations is presented in Table 1 and serves as the basis for the subsequent interpretation of the measurement model results and further analyses.

Table 1: Fit indices of the confirmatory factor analysis (CFA) model

Gen X			**Gen Y**		
Measure	**Standard**	**Scaled/Robust**	**Measure**	**Standard**	**Scaled/Robust**
Estimator	DWLS (WLSMV)		Estimator	DWLS (WLSMV)	
N (observations)	193		N (observations)	244	
Chi-square	418.188	433.623	Chi-square	433.203	474.15
df	213	213	df	213	213
p-value (scaled)		$p < 0.001$	p-value (scaled)		$p < 0.001$
CFI	0.972	0.929	CFI	0.968	0.914
TLI	0.967	0.915	TLI	0.963	0.898
RMSEA	0.071	0.073	RMSEA	0.065	0.071
SRMR	0.092	0.092	SRMR	0.086	0.086
Chi-square (standard)	418.188		Chi-square (standard)	433.203	
df (standard)	213		df (standard)	213	
Chi-square (scaled)		433.623	Chi-square (scaled)		474.15
df (scaled)		213	df (scaled)		213

Source: Authors' own processing in R (lavaan package), based on the survey data

The model was estimated using the WLSMV method, as the analysed variables are ordinal in nature and were measured using Likert scales. This method provides robust parameter estimates and test statistics even in the presence of non-normal response distributions. The results of the confirmatory factor analysis indicate an adequate level of fit between the proposed model and the empirical data in both examined generations. For Generation X, the Comparative Fit Index (CFI) reaches 0.972 in the standard version of the model and 0.929 in the scaled version. The Tucker–Lewis Index (TLI) achieves values of 0.967 (standard) and 0.915 (scaled), suggesting a good level of model fit. For Generation Y, the CFI values are 0.968 in the standard version and 0.914 in the scaled version of the model. The TLI values reach 0.963 (standard) and 0.898 (scaled). These results can also be considered acceptable given the complexity of the model.

The RMSEA values in both generations range from 0.065 to 0.073, indicating an acceptable level of approximation error. Although these values slightly exceed the strict threshold of 0.05, they remain

within the range commonly regarded in the literature as acceptable for models with a higher number of latent constructs and indicators. The SRMR values are below 0.10 in both cases, indicating a good fit between the empirical correlations and those reproduced by the model.

Based on these findings, it can be concluded that the proposed confirmatory factor model is adequately specified in both generations and provides a suitable foundation for further interpretation of factor loadings and comparison of latent constructs between Generations X and Y.

Table 2: Factor Loadings of Indicators in the CFA Measurement Model

Latent construct	Indicator	Unstd. loading (X)	Std.all (X)	Unstd. loading (Y)	Std.all (Y)
DRIVERS	Family reasons (drv_fam)	1	0.692	1	0.648
DRIVERS	Career growth (drv_car)	0.824	0.57	0.986	0.639
DRIVERS	Health and psychological well-being (drv_hea)	1.212	0.839	1.152	0.747
DRIVERS	Work–life balance (drv_wlb)	1.172	0.811	1.199	0.777
DRIVERS	Financial remuneration and benefits (drv_com)	1.226	0.848	1.059	0.687
DRIVERS	Technological conditions (drv_tec)	0.956	0.662	1.096	0.711
BARRIERS	Lack of skills (bar_skl)	1	0.714	1	0.687
BARRIERS	Distrust from supervisors or colleagues (bar_tru)	1.177	0.841	1.126	0.774
BARRIERS	Insufficient employer support (bar_sup)	1.254	0.896	1.438	0.987
BARRIERS	Organisational or legislative constraints (bar_lim)	1.255	0.896	1.204	0.827
PREF_TASKS	Job enlargement (task_ext)	1	0.712	1	0.777
PREF_TASKS	Job enrichment (task_enr)	1.03	0.733	0.898	0.698
PREF_TASKS	Job rotation (task_rot)	0.859	0.611	0.916	0.712
PREF_TIME	Fixed working hours (time_fx)	1	0.588	1	0.573
PREF_TIME	Shift work (time_onc)	0.756	0.444	0.582	0.334
PREF_TIME	Part-time employment (time_prt)	1.288	0.757	0.85	0.487
CONTRACT_REMOTE	Remote work (con_dist)	1	0.734	1	0.801
CONTRACT_REMOTE	Home office (con_home)	0.794	0.582	0.942	0.754
CONTRACT_REMOTE	Telework (con_tele)	1.083	0.795	1.007	0.806

Source: Authors' own processing in R

The table presents the estimates of factor loadings for Generation X and Generation Y within the confirmatory factor analysis. Both unstandardised loadings (Unstd. loading), which are directly estimated in the model, and standardised loadings (Std.all), which allow comparison of the strength of the relationship between individual items and latent constructs as well as comparison of results across generations, are reported.

For the construct BARRIERS (barriers to flexibility), all indicators in both generations achieve moderate to strong standardised factor loadings. In Generation X, the Std.all values range approximately from 0.714 to 0.896, with the highest loadings observed for "Organisational or legislative constraints (bar_lim)" and "Insufficient employer support (bar_sup)". In Generation Y, the standardised loadings range approximately from 0.687 to 0.987, with "Insufficient employer support (bar_sup)" emerging as the strongest indicator. The unstandardised loadings are consistent in both generations, as the reference item within each construct has its loading fixed at 1 and the remaining items are estimated relative to it.

For the construct CONTRACT_REMOTE (remote work preferences), the standardised factor loadings in Generation X range approximately from 0.582 to 0.795, while in Generation Y they range from about 0.754 to 0.806. In both generations, the indicators are adequately associated with the latent construct. In Generation Y, the item "Home office (con_home)" shows a higher standardised loading than in Generation X. The item "Telework (con_tele)" remains the reference indicator in both generations, with its unstandardised loading fixed at 1.

Within the construct DRIVERS (motivational factors of flexibility), the standardised loadings in Generation X range approximately from 0.570 to 0.848 and in Generation Y from 0.639 to 0.806. In Generation X, the highest standardised loading is observed for "Financial remuneration and benefits (drv_com)", whereas in Generation Y the strongest indicator is "Health and psychological well-being (drv_hea)". In both generations, "Work–life balance (drv_wlb)" represents an important indicator, while "Technological conditions (drv_tec)" shows lower, yet still acceptable, standardised loadings.

For the construct PREF_TASKS (preferences for flexibility in job tasks), the standardised factor loadings in Generation X range approximately from 0.611 to 0.733, while in Generation Y they range from about 0.698 to 0.777. This suggests that job enlargement, job enrichment, and job rotation form a consistent measurement of the latent construct in both generational groups.

In the case of the construct PREF_TIME (preferences for working time flexibility), the standardised loadings in Generation X range approximately from 0.444 to 0.757 and in Generation Y from 0.334 to 0.573. The strongest indicator in both generations is part-time employment, whereas the item "Shift work (time_onc)" shows a weaker, yet still acceptable, association with the latent construct, particularly in Generation Y.

Overall, all listed indicators achieve positive and sufficiently high standardised factor loadings in both generations. The proposed measurement model therefore provides a stable and comparable basis for further analysis of relationships among latent constructs and for comparing workforce flexibility preferences between Generation X and Generation Y.

Table 3: Hypothesis testing results in the SEM model – Gen X

Hypothesis	Relationship (arrow)	Estimate (Beta)	SE	t	p-value	Method	Result
H1	CONTRACT_REMOTE → DRIVERS	0.292	0.064	4.581	<0.001	LM	Accepted
H2	CONTRACT_REMOTE → BARRIERS	-0.016	0.066	-0.242	0.809	LM	Rejected
H3	CONTRACT_REMOTE → PREF_TASKS	0.331	0.061	5.395	<0.001	LM	Accepted
H4	CONTRACT_REMOTE → PREF_TIME	0.605	0.032	19.011	<0.001	LM	Accepted
H5	DRIVERS ↔ BARRIERS	0.336	–	–	<0.001	Pearson correlation	Accepted
H6	PREF_TASKS ↔ PREF_TIME	0.504	–	–	<0.001	Pearson correlation	Accepted

Source: Authors' own processing in R

Table 4: Hypothesis testing results in the SEM model – Gen Y

Hypothesis	Relationship (arrow)	Estimate (Beta)	SE	t	p-value	Method	Result
H1	CONTRACT_REMOTE → DRIVERS	0.181	0.052	3.509	5e-04	LM	Accepted
H2	CONTRACT_REMOTE → BARRIERS	0.038	0.05	0.764	0.4454	LM	Rejected
H3	CONTRACT_REMOTE → PREF_TASKS	0.22	0.06	3.635	3e-04	LM	Accepted
H4	CONTRACT_REMOTE → PREF_TIME	0.485	0.029	16.896	<0.001	LM	Accepted
H5	DRIVERS ↔ BARRIERS	0.214	–	–	8e-04	Pearson correlation	Accepted
H6	PREF_TASKS ↔ PREF_TIME	0.689	–	–	0.000	Pearson correlation	Accepted

Source: Authors' own processing in R

H1 (CONTRACT_REMOTE → DRIVERS)

Hypothesis H1 tested whether a higher preference for remote work and alternative contractual forms (CONTRACT_REMOTE) is associated with stronger motivational factors of work flexibility (DRIVERS). This relationship was examined using a linear regression model separately for Generation X and Generation Y. The results revealed a statistically significant and positive relationship in both generational groups. In Generation X, a stronger effect was identified ($\beta = 0.292$, $t = 4.581$, $p < 0.001$) compared to Generation Y ($\beta = 0.181$, $t = 3.509$, $p = 0.0005$). Hypothesis H1 was confirmed in both generations.

H2 (CONTRACT_REMOTE → BARRIERS)

Hypothesis H2 examined whether preference for remote work and alternative contractual forms (CONTRACT_REMOTE) is related to perceived barriers to work flexibility (BARRIERS). The relationship was tested using a linear regression model separately for both generations. The results did not demonstrate a statistically significant relationship in either Generation X ($\beta = -0.016$, $t = -0.242$, $p = 0.809$) or Generation Y ($\beta = 0.038$, $t = 0.764$, $p = 0.445$). Hypothesis H2 was not confirmed in either generational group.

H3 (CONTRACT_REMOTE → PREF_TASKS)

Hypothesis H3 tested the relationship between preference for remote work and alternative contractual forms (CONTRACT_REMOTE) and preference for flexibility in job tasks (PREF_TASKS). The linear regression analysis indicated a statistically significant positive relationship in both generations. In Generation X, a stronger effect was identified ($\beta = 0.331$, $t = 5.395$, $p < 0.001$) compared to Generation Y ($\beta = 0.220$, $t = 3.635$, $p = 0.0003$). Hypothesis H3 was confirmed in both generations.

H4 (CONTRACT_REMOTE → PREF_TIME)

Hypothesis H4 tested whether preference for remote work and alternative contractual forms (CONTRACT_REMOTE) is associated with preference for working time flexibility (PREF_TIME). The regression analysis confirmed a strong and statistically significant relationship in both generations. In Generation X, $\beta = 0.605$, $t = 19.011$, $p < 0.001$, while in Generation Y, $\beta = 0.485$, $t = 16.896$, $p < 0.001$. Hypothesis H4 was confirmed in both generations.

H5 (DRIVERS ↔ BARRIERS)

Hypothesis H5 examined the relationship between motivational factors of work flexibility (DRIVERS) and perceived barriers to flexibility (BARRIERS). As this is a non-directional relationship, it was tested using

Pearson's correlation analysis. The results showed a statistically significant positive correlation in both generations. In Generation X, $r = 0.336$, $p < 0.001$, while in Generation Y, $r = 0.214$, $p = 0.0008$. Hypothesis H5 was confirmed in both generations.

H6 (PREF_TASKS ↔ PREF_TIME)

Hypothesis H6 tested the relationship between preference for flexibility in job tasks (PREF_TASKS) and preference for working time flexibility (PREF_TIME). The relationship was examined using Pearson's correlation analysis. The results revealed a statistically significant positive correlation in both generations, with a stronger correlation in Generation Y ($r = 0.689$, $p < 0.001$) than in Generation X ($r = 0.504$, $p < 0.001$). Hypothesis H6 was confirmed in both generations.

CONCLUSION

This study focused on analysing intergenerational differences in workforce flexibility preferences, with particular attention to Generation X and Generation Y. The aim was to verify the structure of key latent constructs of work flexibility and subsequently examine the relationships between preference for remote work and selected areas of work preferences and attitudes within each generation.

The results of the confirmatory factor analysis confirmed a stable and comparable measurement structure of the latent constructs in both generations, which enabled subsequent hypothesis testing based on factor scores. In both generational groups, sufficiently strong factor loadings of the indicators and an acceptable level of model fit with the empirical data were identified, creating the basis for comparing relationships among the constructs.

The analysis of relationships between preference for remote work (CONTRACT_REMOTE) and other areas of flexibility showed that in both generations this preference represents a significant factor in shaping work preferences. In Generation X as well as in Generation Y, preference for remote work was statistically significantly associated with motivational factors of flexibility, preferences for flexibility in job tasks, and preferences for working time flexibility. At the same time, differences in the strength of these relationships between generations were identified. In Generation X, stronger relationships were found between preference for remote work and preference for working time flexibility, as well as with motivational factors of flexibility. This suggests that for older respondents, the time dimension of flexibility and practical aspects of work organisation play a more prominent role in shaping overall attitudes towards flexible forms of work.

In Generation Y, all of the above relationships were also statistically significant, but generally reached lower intensity compared to Generation X in terms of direct links to remote work. On the other hand, younger respondents demonstrated stronger interconnections among the individual dimensions of flexibility. In particular, the relationship between preferences for flexibility in job tasks and preferences for working time flexibility was stronger in Generation Y than in Generation X, indicating a more integrated and multidimensional perception of flexibility as a whole.

The relationship between preference for remote work and perceived barriers to flexibility was not confirmed as statistically significant in either generation. This result suggests that barriers to flexibility do not represent a decisive factor in shaping preference for remote work in either Generation X or Generation Y, and that their perception is largely independent of preferences for remote forms of work.

Positive and statistically significant relationships were also identified among the latent constructs themselves. In both generations, a positive association was found between motivational factors and barriers to flexibility, as well as between preferences for flexibility in job tasks and working time flexibility. However, the strength of these relationships was in several cases higher in Generation Y, indicating a greater internal consistency of flexibility preferences among younger employees.

Overall, the results show that although Generation X and Generation Y share a similar structural pattern of workforce flexibility preferences, differences exist in the strength and character of relationships among individual areas of flexibility. While time-related and practical aspects of flexibility appear to play a

more dominant role in Generation X, flexibility preferences in Generation Y seem to be more multidimensional and interconnected across various aspects of working conditions.

The findings highlight the need for a differentiated approach to managing workforce flexibility with regard to generational specificities. The results suggest that flexible working conditions should not be designed uniformly for all employees but should instead reflect differing preferences and mechanisms underlying flexibility in individual generations. At the same time, the findings open space for further research aimed at extending the analysed model with additional determinants of work preferences and verifying its validity in a broader demographic and sectoral context. The study also contributes to the theoretical discussion on generational workforce differences by empirically validating a multidimensional measurement model of work flexibility across generational cohorts.

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DETERMINANTS OF ARTIFICIAL INTELLIGENCE ADOPTION IN HIGHER EDUCATION: AN IMPORTANCE–PERFORMANCE MAP ANALYSIS APPROACH

Dana Jašková

Abstract

Rapid advancements in artificial intelligence (AI), particularly Generative AI, are fundamentally transforming higher education. The aim of this study is to identify the determinants of AI acceptance among Generation Z students and to extend existing technology adoption models by integrating the methods of Partial Least Squares Structural Equation Modeling and Importance–Performance Map Analysis. Empirical data were collected through a questionnaire survey conducted among university students. The model included Perceived Informedness, Perceived Knowledge, Perceived Usefulness, and Perceived Risk. The Partial Least Squares Structural Equation Modeling results confirmed the significance of Perceived Knowledge and Perceived Usefulness, while Perceived Risk was not found to be significant. The Importance–Performance Map Analysis revealed that Perceived Knowledge represents the most important and best-developed factor, whereas Perceived Usefulness constitutes the key area for improvement. Perceived Informedness shows a limited impact despite its relatively high level of performance. The findings highlight the need to focus on the practical applicability of AI as the primary driver of its adoption in the higher education environment.

Key words:
Generative Artificial Intelligence, Higher Education, Adoption models, PLS-SEM, IPMA

JEL Classification O33, C83, I23
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INTRODUCTION

In recent years, education has been undergoing a transformation driven by digitalization and modern technologies. Technology increasingly permeates processes such as information handling, the organization of learning, and the preparation of students for life in a digitally integrated world. Generative AI (GAI) is rapidly entering this domain, becoming easily accessible and widely used by both students and educators, often beyond formally established rules. Its development not only affects how learning and teaching are conducted but also reshapes the roles of students and teachers while increasing demands on educational management. Artificial Intelligence (AI) refers to systems capable of performing tasks that traditionally require human intelligence, such as learning, decision-making, and information processing (Holmes, 2023). Its rapid development contributes to broader societal changes reflected in education, raising concerns about responsible use, reliability, and transparency. For educational management, it is therefore essential not only to monitor technological capabilities but also to understand their implications for learning processes and institutional outcomes (Miao & Holmes, 2021; Slavov et al., 2023). A clearly defined understanding of AI is crucial, as it influences technology selection, governance, and the development of student competencies.

The rapid diffusion of GAI into education has created a paradox in both policy and practice: while institutions embrace its potential for personalization, automation, and improved access, they simultaneously face risks related to privacy, academic integrity, and inequality. Its implementation requires clear guidelines, adapted assessment mechanisms, and continuous professional development of educators. Governance should also define responsibility for tool selection, use, and oversight (Grandström & Oppi, 2025; Miao & Holmes, 2021). UNESCO (2023) issued the first

global guidance on generative AI in education, emphasizing ethical use, data protection, and human-centered approaches, while OECD highlights that most countries rely on non-binding guidelines, shifting responsibility to institutions. Existing research points to both opportunities (e.g., personalization and enhanced feedback) and risks (e.g., integrity and digital inequality), underscoring the need for theoretically grounded empirical models explaining AI adoption and continued use.

The aim of this study is to examine the determinants of AI adoption in higher education by combining Partial Least Squares Structural Equation Modeling with Importance–Performance Map Analysis, enabling not only the identification of significant relationships but also the assessment of their practical relevance. This study contributes to the literature by demonstrating that the gap between perceived knowledge and perceived usefulness represents a critical barrier in AI adoption, which is not captured by traditional TAM-based models.

LITERATURE OVERVIEW

Generative AI tools accelerate information retrieval, summarization, and data processing. In doing so, they contribute to higher productivity and more efficient utilization of human resources (U.S. Government Accountability Office, 2023; Uddin et al., 2025). These tools is becoming a factor that shapes the direction of organizations and their approaches to change management. In the field of education, GAI is being adopted at an exceptionally rapid pace. Generative tools are now widely accessible, and students increasingly rely on them in their studies, often even without the formal integration of AI into the curriculum. GAI influences learning processes, students' approaches to working with information, and their strategies for solving academic tasks (Miao & Holmes, 2021). Students use GAI tools for language editing, translation, writing support, explaining subject matter, and checking assignments (Granström & Oppi, 2025). From a teaching perspective, these tools can support the creation and adaptation of learning materials and help tailor content to the individual needs of students (Uddin et al., 2025). However, the rapid diffusion of GAI in educational settings also creates new challenges for institutions. There is an increasing need to establish clear rules for the use of AI and to make informed decisions regarding the integration of generative tools into education. Therefore, the practical use of GAI must be closely linked with issues of control, accountability, and technological limitations (Uddin et al., 2025; Sengar et al., 2024).

The field of education is undergoing a transformation under the influence of digitalization and modern technologies. The use of technology increasingly permeates processes such as information handling, the organization of learning, and the preparation of students for life in a world where digital technologies are an integral part of everyday reality (Slavov et al., 2023). GAI is entering this development at a rapid pace, as it is easily accessible and both students and educators have already begun to use it in practice, often beyond formally established rules. Its development is reshaping the roles of both students and teachers within the educational process and increasing the demands placed on the management of educational processes. Educational management encompasses the planning, organization, implementation, and evaluation of educational activities at the level of institutions, educational systems, or specific programs. In recent years, it has been increasingly influenced by digital transformation, of which AI has become an integral component. Its implementation does not represent merely a technological innovation, but also a transformation of educational processes themselves. For this reason, GAI is already becoming a subject of strategic management within educational institutions (Miao & Holmes, 2021). The rapid proliferation of generative tools is placing increasing pressure on educational institutions to respond systematically. GAI can therefore no longer remain solely an individual initiative of teachers or students, but requires a coordinated and managed approach from institutional leadership. It is necessary to determine how Artificial Intelligence should be integrated into the educational process. A distinction must be made between the use of AI in teaching and

administration, and education about AI as part of the curriculum. In the first case, AI serves to support teaching, the preparation of materials, and the streamlining of administrative processes. In the second case, the focus is on developing an understanding of how AI works, its limitations, and its impact on society (Holmes, 2023). The implementation of GAI requires the establishment of clear usage guidelines, the adaptation of assessment mechanisms, and the professional development of educators. An essential component of governance is also the definition of responsibility for the selection of tools, the manner of their use, and the oversight of their application. Clearly defined processes help prevent ambiguity and can strengthen trust in institutional decision-making (Granström & Oppi, 2025; Miao & Holmes, 2021). The development of AI technologies also highlights the need to systematically build competencies among both students and educators. Educational management thus faces the challenge of maintaining a balance between the innovative potential of these tools and the need for clear rules, oversight, and data protection. Once these frameworks are established, it becomes possible to evaluate the actual benefits for teaching and learning.

The implementation of GAI has the potential to influence both learning processes and the functioning of educational institutions. Strategic documents of the European Union and UNESCO primarily emphasize benefits for students, who are at the center of the educational process. However, the impact of GAI also extends to teachers and institutional management; therefore, its implementation should take into account the broader organizational context (Slavov et al., 2023). One of the most frequently cited benefits is the personalization of learning, particularly through Self-Directed Learning (SDL) tools, which enable the adaptation of content, difficulty, and pace of instruction to individual student needs. This is expected to enhance flexibility and the ability to respond to diverse learning styles (Miao & Holmes, 2021). Another important area is the support of academic writing and access to information. The use of GAI in education brings a range of risks and challenges that must be taken into account. These relate to technological limitations as well as ethical, pedagogical, and organizational aspects. The implementation of generative tools should therefore not be automatically perceived as beneficial, but rather as a process requiring carefully designed policies and continuous evaluation of impacts (Granström & Oppi, 2025; Holmes, 2023). One of the most widely discussed issues is academic integrity. GAI enables the generation of texts, program code, and solutions to assignments, which may have significant negative implications for student autonomy. Unintentional plagiarism, as well as the deliberate misuse of such tools, represents a risk that necessitates the establishment of appropriate assessment mechanisms and clear usage guidelines. Research points to concerns about the weakening of critical thinking and creativity when AI tools are overused. In student learning, it is essential that learners engage in phases of planning, ongoing monitoring, and self-reflection. GAI can support these phases, for example, by explaining subject matter or helping to organize the learning process, but it can also bypass them by providing immediate solutions without requiring deeper cognitive processing. There are also concerns regarding the uncritical adoption of generated content without verification, the spread of inaccuracies caused by model hallucinations, and weaker evaluation of sources underlying generated information (Granström & Oppi, 2025).

Some studies also point to social and psychological factors. Excessive use of AI tools may limit direct interactions between students and teachers, as well as among students themselves. When communication is replaced by technology, feelings of isolation or weaker integration into the educational environment may emerge (Granström & Oppi, 2025). At the same time, the pace of development of Artificial Intelligence tools exceeds the capacity of educational systems to provide sufficient support to educators. Teachers may experience uncertainty, particularly when responding to the widespread use of AI by students. Another open question concerns the extent of the empirical foundation for implementing AI in education. Although research on its use is increasing, large-scale and independent studies on its long-term impact on educational outcomes remain limited. This reinforces the need for caution when shaping expectations and designing implementation strategies (Holmes, 2023). The challenges associated with GAI in education highlight the need for a long-term vision grounded in evidence, continuous evaluation of impacts,

and clearly defined accountability (Miao & Holmes, 2021). The risks are closely linked to ethical and regulatory issues surrounding its use. Questions of regulation concern not only legislation, but also ethical principles, internal institutional policies, and the ways in which institutions protect students when working with GAI (Bellas et al., 2023). A portion of the recommendations and frameworks originates from the international and European context and is subsequently translated into national policies and specific school-level regulations. For this reason, UNESCO emphasizes the need for coherent direction, rules, and procedures that support educational objectives and the ethical use of GAI (Bellas et al., 2023). A significant development in this area is the Artificial Intelligence Act, which establishes a legal framework for the development, deployment, and use of AI systems within the European Union. The AI Act is based on a risk-based approach. This means that the higher the level of risk a particular system poses, the stricter the rules that apply to it (Kop, 2021). The AI Act also demonstrates that, although something may be technologically feasible, it is not necessarily acceptable within the educational context (Regulation (EU) 2024/1689, 2024).

International organizations and academic literature emphasize transparency, accountability, fairness, and privacy protection in the use of AI systems in education (Granström & Oppi, 2025; Sengar et al., 2024). A key ethical issue also concerns how GAI handles student data and where the boundaries of acceptable use lie. In the educational context, this is not only about technical data protection, but also about trust, awareness, and careful handling of data related to students' performance, behavior, and activities. The issue is not merely whether data are formally protected, but also whether they are used sensitively and with respect for students (Sengar et al., 2024). Closely related to regulation and ethics is the development of AI literacy. Beyond establishing rules and highlighting risks, it is essential that students and educators understand what Artificial Intelligence can do, where its limitations lie, and how to critically assess when its outputs should be verified or questioned. The development of AI literacy can help prevent the use of AI without sufficient understanding of its capabilities, limitations, and associated risks (Miao & Holmes, 2021; Hornberg et al., 2023).

AI Literacy represents a broader set of knowledge, skills, and attitudes that enable individuals to understand how GAI works and to use it appropriately. It includes an understanding of the fundamental principles of AI, the ability to critically evaluate its outputs, and the capacity to apply this knowledge across different contexts (Kong et al., 2021; Dai et al., 2020). As part of students' digital competencies, AI literacy is recommended to be integrated into curricula. However, this does not imply merely introducing it as a standalone topic or providing one-time exposure to tools. Rather, it is a competence that should be developed continuously and interconnected with other subjects and areas of education. For this reason, UNESCO recommends that AI should appear not only in computer science education but also in subjects where there is scope to address its societal impact, ethical considerations, and practical implications for everyday life. Reviews of research on AI in higher education highlight both opportunities (enhanced feedback and personalization) and persistent concerns (academic integrity and digital inequality). They therefore emphasize the need for theoretically grounded empirical models that explain whether and why students adopt AI and why they continue to use it (Kasneci et al., 2023). More recent studies reinforce these issues: Dwivedi et al. (2023) point to the transformative yet disruptive potential of ChatGPT; Rudolph et al. (2023) highlight implications for traditional assessment; Mhlanga (2023) stresses the need for responsible implementation; Holmes et al. (2022) call for ethical frameworks; and Tlili et al. (2023) examine the paradoxical role of chatbots in education.

Existing adoption research primarily relies on the Technology Acceptance Model (TAM) and the Theory of Planned Behavior (TPB), which capture perceived usefulness, ease of use, social norms, and control, but tend to overlook motivational needs that support long-term use. One of the more recent studies by Tbaishat et al. (2026) examines the acceptance of GAI in higher education using an integrated TAM–TPB–SDT framework, where Self-Determination Theory (SDT) is incorporated. The findings indicate that adoption is shaped not only by cognitive evaluations, such as perceived usefulness and ease of use, but also by motivational needs, namely autonomy, competence, and social influences. The development and examination of integrated models of GAI

acceptance in higher education, involving all relevant stakeholders, is currently of critical importance. The results of these studies provide concrete recommendations for universities: to design AI-supported collaborative learning activities that foster relatedness, to invest in the development of digital competencies that enable confident use, and to provide students with autonomy in integrating AI into their academic work. At the same time, these findings confirm the value of integrating cognitive, social, and motivational perspectives in explaining AI adoption.

METHODOLOGY

Research Design, Conceptual Model, and Sample

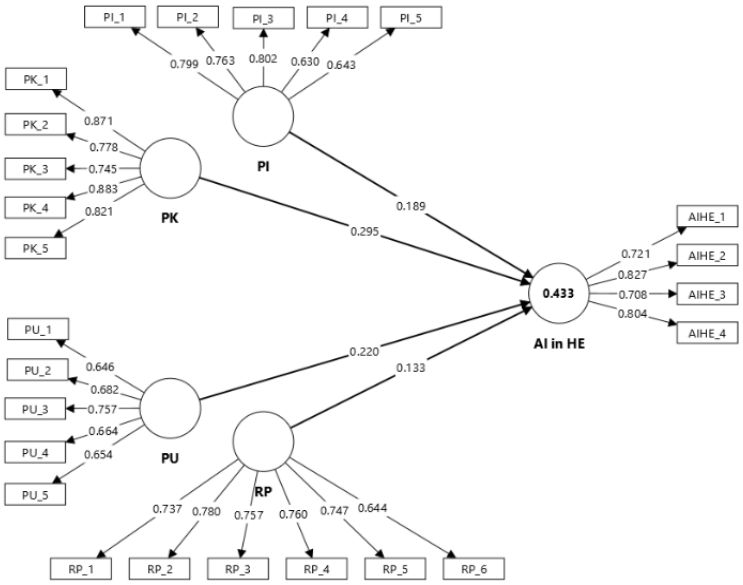
The present study builds on prior research in which a model of the determinants of Artificial Intelligence adoption in higher education was tested using Partial Least Squares Structural Equation Modeling.The conceptual model consists of five latent constructs and their causal relationships. The dependent variable of the model is the construct Artificial Intelligence in Higher Education (AI in HE), which represents the level of acceptance and perception of the use of AI technologies in education. This construct is influenced by four exogenous variables: Perceived Informedness (PI), Perceived Knowledge (PK), Perceived Usefulness (PU), and Perceived Risk (RP). The model was tested as a reflective structural model with direct relationships between the individual constructs. Building on these results, the objective of the present study is to extend the interpretation of the model using IPMA, which enables the identification of key factors in terms of their importance and performance. The IPMA map provides a more detailed interpretation of the structural model by simultaneously considering both the importance and the performance of individual constructs.

The research sample consisted of respondents belonging to Generation Z, representing a digitally native population with a high level of exposure to modern technologies. Data collection was conducted online using the Computer-Assisted Web Interviewing (CAWI) method. The sample size comprised 130 respondents, with a response rate of 71%.

Operationalization of Constructs

The questionnaire was developed based on established theoretical models of technology adoption, particularly the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), which were adapted to the context of AI technologies. The measurement instrument followed a multi-item approach, with individual constructs operationalized through items adopted and adapted from relevant literature. The questionnaire consisted of 25 items, with each construct measured by multiple indicators. Respondents evaluated each statement using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The model of identified and statistically significant causal relationships is presented in the following figure.

Figure 1: Semantic model



Source: Author's own elaboration

The resulting model was first assessed in terms of the measurement model using Convergent validity (Loadings, AVE), Internal Consistency reliability (Cronbach´s α, reliability ρ_A, reliability ρ_C) and Discriminant validity (FL criterion, HTMT, VIF). Subsequently, the structural model was evaluated using the coefficient of determination (R^2), effect size (f^2), Path Coefficient (β), and T-statistic values, as well as the predictive relevance of the model (Q^2). The predictive power of the estimated model was assessed using the Q^2 statistic, which is appropriate for reflective measurement models. The value obtained for Q^2 (AI in HE) was 0.381, which, according to Hair et al. (2024), indicates excellent predictive power of the model. The difference between RMSE values for PLS-SEM and linear modeling (LM) was negative, indicating that PLS-SEM produces a lower prediction error compared to LM.

Based on the validated model, the Importance–Performance Map Analysis (IPMA) method was applied in order to extend the interpretation of the results. The IPMA (also called Importance-performance matrix, impact-performance map, or priority map analysis) extends the standard results reporting of path coefficient estimates and other parameters by adding a procedure that considers the average values of the construct scores (Hair et al., 2024). The IPMA contrasts the total effects, representing the predecessor construct´s importance in predicting a specific target construct, with their average construct scores indicating their performance. The rationale is to identify predecessor constructs that have a relatively high importance for explaining the target construct (those that have a strong total effect), but also have a relatively low performance (low average construct scores), so that improvements can be implemented. The IPMA draws on the five step procedure: Requirement check, Computation of the performance values, Computation of the importance values, Importance-performance map creation, Extension of the IPMA on the indicator´s level (Ringle, Sarsted, 2021).

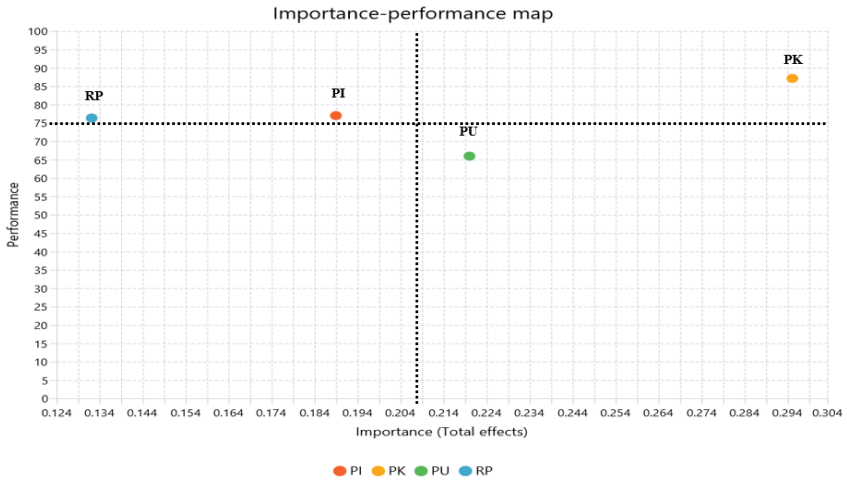
For the analyzed model, Importance–Performance Map Analysis (IPMA) was conducted for the dependent construct AI in HE. Importance was determined based on the total effects of the exogenous variables: Perceived Informedness (PI), Perceived Knowledge (PK), Perceived Usefulness (PU), and Perceived Risk (RP) on AI in HE. Performance was calculated as the mean

values of the latent variables, transformed to a 0–100 scale. This approach enables the identification of factors with a high impact on AI acceptance (e.g., PK, PU), areas with improvement potential (high importance but lower performance), and less relevant factors (e.g., RP in this model). The IPMA results thus represent a practical tool for formulating managerial recommendations in the implementation of AI in education.

FINDINGS

The figure presents IPMA results for the target construct AI in HE obtained using SmartPLS.

Figure 2: IPMA (construct level) for target construct independent constructs and its indicators



Source: Author's own elaboration

The horizontal axis represents the performance of the latent constructs, rescaled to a range from 0 to 100, while the vertical axis captures their importance, expressed as total effects derived from the PLS-SEM model. The map is divided into four quadrants based on the mean values of importance (0.209) and performance (76.61). The construct Perceived Knowledge (PK) is located in the quadrant with high importance and high performance, indicating a key strength of the model. The factor Perceived Usefulness (PU) falls into the quadrant with high importance but lower performance, identifying it as the most critical area for improvement. The construct Perceived Informedness (PI) is positioned in the quadrant with lower importance and higher performance. This suggests that although respondents perceive themselves as well-informed, this factor has a limited impact on the acceptance of Artificial Intelligence.

Finally, the construct Perceived Risk (RP) is located in the quadrant with low importance and low performance, indicating its marginal role in explaining the adoption of AI technologies.

The IPMA results provide (Table 1) an extended interpretation of the tested hypotheses by integrating both the statistical significance (PLS-SEM) and practical relevance (importance–performance).

- H1 (PI → AI in HE) was supported in the PLS-SEM model; however, IPMA reveals that despite relatively high performance, Perceived Informedness has only moderate importance. This indicates that increasing awareness alone may not substantially enhance AI adoption.

Table 1: IPMA results for AI in HE

Construct	Importance (Total Effect)	Performance (0–100)	Hypothesis	PLS-SEM Result	IPMA Interpretation
Perceived Knowledge (PK)	0,295	87,13	H2	Supported	Key strength (maintain)
Perceived Usefulness (PU)	0,220	65,96	H3	Supported	Priority for improvement
Perceived Informedness (PI)	0,189	77,00	H1	Supported	High performance, limited impact
Risk Perceived (RP)	0,133	76,34	H4	Not supported	Low priority factor

- H2 (PK → AI in HE) was strongly supported and confirmed as the most influential relationship. IPMA further shows that Perceived Knowledge combines high importance with high performance, identifying it as a well-established and stable determinant of AI acceptance.
- H3 (PU → AI in HE) was supported and identified as a significant predictor. Importantly, IPMA highlights Perceived Usefulness as the most critical improvement area, as it exhibits high importance but comparatively lower performance.
- H4 (RP → AI in HE) was not supported, which is consistent with IPMA results indicating low importance and low performance. This confirms that perceived risk does not represent a key barrier to AI adoption in the studied sample.

The combined interpretation of Partial Least Squares Structural Equation Modeling and Importance–Performance Map Analysis demonstrates that statistical significance alone is not sufficient for managerial decision-making. Although several relationships were confirmed, only selected constructs,particularly Perceived Usefulness (PU), offer substantial potential for improving AI adoption outcomes. The results clearly show that importance and performance do not necessarily align. While Perceived Knowledge (PK) is both highly important and well developed, Perceived Usefulness (PU) emerges as the only construct with a strong impact but insufficient performance, making it the primary target for intervention.

DISCUSSION

The aim of this study was to extend the understanding of Artificial Intelligence (AI) adoption in higher education by integrating Partial Least Squares Structural Equation Modeling (PLS-SEM) with Importance–Performance Map Analysis (IPMA). While PLS-SEM identified statistically significant relationships, IPMA added a practical dimension by linking these relationships to their relative importance and performance, thereby enabling more actionable interpretation. The findings are consistent with the Technology Acceptance Model (TAM), particularly regarding the central role of Perceived Usefulness (PU) as a key determinant of technology adoption. However, this study extends the traditional TAM perspective by demonstrating that perceived usefulness alone is insufficient unless it is supported by actual performance. The IPMA results reveal a critical gap: although PU has a strong impact on AI adoption, its performance remains relatively low. This suggests that students recognize the potential value of AI, but this value is not yet fully reflected in their learning experience.

A key contribution of this study lies in distinguishing between Perceived Knowledge (PK) and Perceived Usefulness (PU). While PK demonstrates both high importance and high performance, indicating that Generation Z students possess a well-developed understanding of AI technologies, PU represents a gap between potential and actual value. This finding suggests that knowledge does not automatically translate into meaningful use. Students may be capable of using AI tools, yet they do not necessarily perceive them as sufficiently beneficial in their academic work. The strong effect of PK is consistent with extended models such as UTAUT, where user competence plays a significant role. However, the results indicate that in digitally mature populations, knowledge is no longer a limiting factor. Instead, the key challenge lies in transforming this knowledge into perceived usefulness and practical value. This reflects a shift in adoption research from issues of access and awareness toward integration and effective use.

Perceived Risk (RP) was not found to have a significant effect on AI adoption, which contrasts with prior research emphasizing risk as a key barrier. This result can be explained by the characteristics of Generation Z, which tends to exhibit lower sensitivity to technological risks. The IPMA results further confirm that RP has low importance, suggesting that risk does not represent a priority for intervention. Similarly, Perceived Informedness (PI) shows relatively high performance but limited importance, indicating that being informed about AI does not necessarily lead to its adoption. This highlights a common limitation in adoption research: information alone is insufficient to drive behavior. In the context of AI, this suggests that strategies focused solely on awareness are unlikely to significantly increase adoption. From a theoretical perspective, the study contributes by integrating IPMA into technology adoption research and by identifying a critical gap between knowledge and usefulness. The findings suggest that the main barrier to AI adoption is not a lack of awareness, but the insufficient translation of AI capabilities into meaningful value. From a practical perspective, higher education institutions should move beyond awareness-building and focus on demonstrating the tangible benefits of AI in learning. This includes integrating AI tools into curricula, providing structured use cases, and supporting students in applying AI in real academic tasks. Overall, the study shows that the key challenge in AI adoption is not knowledge, but usefulness, and the ability to translate AI potential into meaningful educational outcomes.

Limitations

Despite its contributions, this study has several limitations that should be taken into account. The research is based on a relatively small sample of university students (n = 130), which may limit the generalizability of the findings. Furthermore, the study relies on self-reported data, which may be affected by Common Method Bias and social desirability effects. Respondents may overestimate their knowledge or provide answers that align with expectations rather than reflect their actual behavior. The research employs a cross-sectional design, which does not allow for the observation of changes in Artificial Intelligence adoption over time. Given the rapid development of AI technologies, user perceptions and behaviors may evolve dynamically. The model focuses on selected constructs derived from established technology acceptance frameworks, such as the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT). Other potentially relevant factors, such as social influence, institutional support, or ethical considerations, were not included in the model. The study focuses on cognitive determinants and does not capture behavioral intention or actual usage behavior.

CONCLUSION

The aim of this study was to examine the determinants of AI adoption in higher education by combining PLS-SEM and IPMA. While the structural model identified statistically significant relationships, the IPMA approach provided deeper insights into their practical relevance. The findings confirm that Perceived Knowledge (PK) represents the strongest and most developed

determinant of AI adoption among Generation Z students. At the same time, Perceived Usefulness (PU) emerged as the most critical factor for improvement, as it combines high importance with relatively lower performance.

This suggests that the key challenge in AI adoption is not a lack of awareness or knowledge, but rather the insufficient translation of AI capabilities into perceived practical value. Furthermore, the study shows that Perceived Informedness (PI), despite its relatively high level, does not significantly influence adoption, while Perceived Risk (RP) does not represent a major barrier. These findings indicate the need to shift attention away from information-based and risk-oriented approaches toward strategies that emphasize practical benefits and meaningful use of Artificial Intelligence in educational contexts. Overall, the study demonstrates that the combination of PLS-SEM and IPMA provides a more comprehensive understanding of technology adoption by linking statistical significance with practically actionable insights. Future research can build on this study in several directions. First, to enhance the generalizability of the findings, larger and more diverse samples should be employed. Comparative studies across different countries, educational systems, or age groups could provide a broader understanding of AI adoption patterns. Second, longitudinal research designs would enable the analysis of how perceptions of AI evolve over time, particularly in response to increasing exposure and technological advancement. Third, future studies could extend the model by incorporating additional variables such as social influence, facilitating conditions, trust, or perceived ethical concerns, thereby achieving a more comprehensive understanding of the factors influencing AI adoption. Fourth, qualitative approaches could complement quantitative findings by exploring how students actually use AI tools in their learning processes. Such insights could help explain the identified gap between Perceived Knowledge and Perceived Usefulness.

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THE IMPACT OF HUMAN CAPITAL ON THE COMPETITIVENESS OF COUNTRIES IN THE CENTRAL AND EASTERN EUROPEAN REGION (CEE)

Eva Koišová, Veronika Žárská

Abstract

In Central and Eastern European (CEE) countries, competitiveness is a pivotal factor given its impact on economic growth, the capacity to attract foreign investment, and integration into global markets. Human capital, defined as the aggregate of an individual's education, health, and skills, is a critical factor in determining competitiveness. It exerts a substantial influence on productivity, the innovative capacity of economies, and their capacity to achieve sustainable economic growth. The primary objective of the present study was to examine the relationship between human capital and the competitiveness of economies in Central and Eastern European countries. To this end, the V4 countries were compared with other countries in the region, the growth dynamics of selected indicators were analyzed, convergence trends were examined, and a regression analysis was performed on the relationship between these indicators in individual countries. To achieve this objective, a variety of scientific methods were employed. The Mann-Whitney U test was employed to compare the V4 countries with other countries in the region, while the dynamics of HDI and WCI development were assessed using the average growth coefficient. The sigma convergence method was employed to identify convergence trends, and the relationship between the HDI and WCI levels in individual countries was examined using the simple linear regression method, supplemented by the Durbin-Watson test. The findings indicated that the V4 countries are comparable to other countries in Central and Eastern Europe with regard to competitiveness and human capital. The σ-convergence results did not demonstrate a discernible convergence or divergence trend between countries. The application of regression analysis revealed a statistically significant impact of human capital on competitiveness in the Czech Republic and Estonia. In contrast, the majority of countries exhibited a weak or insignificant relationship between human capital and competitiveness, indicating the necessity of considering additional factors that influence competitiveness.

Key words:
Central Eastern Europe, Competitiveness, Human capital, Human Development Index, World Competitiveness Index

JEL Classification I23, I25, Z32, M53, J24 https://doi.org/10.52665/ser20260103

INTRODUCTION

The European Union and other European countries are currently facing complex challenges in maintaining and strengthening their competitiveness. The impact of climate change, the emergence and dynamic development of artificial intelligence, and ongoing geopolitical tensions on the quality of life and economic stability and resilience of individual countries are significant. To ensure long-term success in this shifting landscape, it is imperative that Europe maintains its position as a catalyst for sustainable growth, innovation, and technological advancement, underpinned by the optimal utilization of human capital.

In response to these challenges, the countries of Central and Eastern Europe (CEE) have a special role to play, having undergone significant dynamic development over the past two decades. Initially, they established themselves primarily as a manufacturing base for the European Union and attracted a significant amount of foreign direct investment from Western Europe. Consequently, they have been progressively converging towards the EU's mean income level, concurrently embarking on a broadening of their economic portfolio, with a strategic emphasis on the advancement of the service sector and the promotion of activities characterized by elevated

added value. Ferrazzi et al (2024) have noted that several scientific and professional authorities have gradually begun to focus on the contribution of CEE countries and the competitiveness of the EU. They have also cited studies that provide further insights into the competitiveness and contribution of human capital in the Central and Eastern European region (Jazwinski, 2024; Ferrazzi et al 2025).

The Central and Eastern European (CEE) region is comprised of eleven countries: the Czech Republic, Slovakia, Poland, Hungary, Slovenia, Estonia, Latvia, Lithuania, Romania, Bulgaria, and Croatia. These countries constitute the sample for the present research. The primary objective of the present study was to examine the relationship between human capital, measured by HDI, and the competitiveness of economies, measured by WCI, from 2014 to 2023 in Central and Eastern European countries. To this effect, the V4 countries were compared with other countries in the region, the growth dynamics of selected indicators were analyzed, convergence trends were examined, and a regression analysis of the relationship between these indicators in individual countries was performed.

Despite the extensive literature devoted to human capital and economic growth, knowledge about the impact of human development on national competitiveness in Central and Eastern European (CEE) countries remains limited in the long term. A notable absence in the extant literature is empirical analyses based on panel data that would link the Human Development Index (HDI) and the World Competitiveness Index (WCI) within a unified analytical framework. In this context, longitudinal evidence comprises studies that systematically track the development of specific countries over time. This methodological approach enables the capture of the dynamics inherent in the relationship between human development and competitiveness, including potential lagged effects.

Despite the existence of numerous studies that have examined the relationship between human capital and the competitiveness of economies (see Bak et al., 2022; Gaona & Vásquez, 2021; Debrah, 2018, among others), the extent to which this relationship is manifested at the level of individual countries in the Central and Eastern European region, and whether the intensity of this relationship is uniform across all countries in the region, remains under-explored. Existing studies have focused on comparing old and new EU member states (Tijanic & Obadic, 2015) or have employed aggregated panel approaches (Cetinguc et al., 2023). However, these approaches may obscure specific national characteristics. However, there is a paucity of attention devoted to the integration of dynamic, convergence, and simple regression analysis at the individual country level, as well as the comparison of the V4 countries with other countries in the region. The present study aims to contribute to a deeper understanding of the role of human capital in shaping the competitiveness of Central and Eastern European economies. In addition, it seeks to identify differences in the strength of this relationship between individual countries in the region.

LITERATURE OVERVIEW

The concept of competitiveness has emerged as a prominent theme in the realm of professional literature. It has garnered significant attention from European Union representatives, as well as from the professional public and economic actors. This attention is attributed to the perception of competitiveness as a pivotal catalyst for economic growth, prosperity, and sustainable development. The professional public has long focused on examining the competitiveness of companies and national economies. However, the concept of regional competitiveness is a relatively new approach that is the subject of diverse interpretations and discussions. Some authors have even raised questions regarding the very applicability of the concept of competitiveness at the regional level. According to Krugman (1997), the employment of the term "competitiveness" within the context of regional economics can be problematic, as it may result in erroneous policy conclusions. The primary rationale for this phenomenon is the inherent complexity of defining regional competitiveness in a definitive manner, given the

multifaceted nature of regions as economic and social entities (Žitkusa, 2015). However, Staníčková (2019) asserts that only a systematic and thorough analysis grounded in multiple research approaches can yield a conceptually anchored definition and a reliable assessment of regional competitiveness. Conversely, several authors posit that regional competitiveness is a legitimate concept, provided it is understood as the capacity of a region to support economic activity and ensure the relative prosperity of its population (Begg, 1999; Huovari, Kangasharju & Alanen, 2000). Annoni & Dijkstra (2019) define regional competitiveness in this context as the ability of a region to provide businesses and residents with an attractive and sustainable environment for living and working, while reconciling the goals of economic success with social well-being and emphasizing both short-term and long-term sustainability. This approach also differentiates between the determinants of competitiveness (e.g., quality of human capital, innovation potential, accessibility, agglomeration effects) and its outputs (e.g., GDP per capita, income level, employment).

Huovari, Kangasharju, & Alanen (2000) similarly highlight the necessity of comprehending this concept in a more expansive manner, extending beyond the mere measurement of outcomes. They underscore that it encompasses the prerequisites for development and the capacity of the regional system to function efficaciously. Palinchak et al. (2021) posit that a region's high competitiveness is the result of effective organization and optimization of economic processes, the existence of adequate infrastructure, a functional institutional environment, and the effective activity of market actors. According to Wokoun (2016), the determination of regional competitiveness is not solely determined by production indicators. The structure of production, production capacities, innovation characteristics, the quality of the workforce, and the settlement structure are also factors that contribute to regional competitiveness. Huggins et al. (2014) posit that companies and their market position are pivotal factors in regional competitiveness, as companies are the primary drivers of knowledge creation, innovation, and new jobs. The degree of regional competitiveness is, to a considerable extent, contingent on the existence of conditions that facilitate the ability of companies to compete in both domestic and international markets. Wokoun (2016) further posits that a region is competitive if it is attractive to investors, entrepreneurs, and the transfer of know-how. In their 2019 study, Borovitskaya et al. characterized regional competitiveness as the ability of a region to succeed in competition with other regions. The factors that contribute to this success include population growth, innovation activity, and intellectual potential development. The study also identified factors that increase investment attractiveness, reduce socio-economic disparities, and improve the quality of life of the population. Kouskoura et al. (2024) identified ten primary domains of regional competitiveness through an exhaustive review of the extant literature. These domains include the economy, labor market, poverty and social inclusion, healthcare, educational infrastructure, environmental conditions, transport infrastructure, science and technology, high-tech industries, and innovation.

In Central and Eastern European (CEE) countries, competitiveness is a pivotal factor because it influences economic growth, the ability to attract foreign investment, and integration into global markets. The countries of Central and Eastern Europe (CEE) have shared historical experience of post-communist transformation and are now members of the European Union. The competitiveness of these countries is influenced by various historical, economic, and social factors. As previously stated, the Central and Eastern European countries that are members of the European Union (EU) include the following: Bulgaria, Croatia, the Czech Republic, Hungary, Poland, Romania, Slovakia, and Slovenia, as well as the Baltic countries of Estonia, Lithuania, and Latvia. Collectively, these nations have a population exceeding 100 million. The CEE countries do not constitute a region in the administrative sense; however, in the professional literature and research works of many authors (Gorzelak & Smętkowski, 2010; Pellényi, 2020; Holobiuc, 2021; Török, 2025; Rácz et al., 2025), they are often understood as a macro-region used for analytical and comparative purposes, as they share similar historical, economic, and institutional characteristics.

In recent years, the European Union has placed a premium on enhancing its competitiveness in order to address its deteriorating position in the global economy and the growing challenges posed by technological and geopolitical rivalry. Europe is particularly confronted with a lag in productivity growth and in the capacity to support innovative businesses when compared to the United States and China. This is evident in lower innovation dynamics, weaker development of digital technologies, and constrained access to venture capital (European Commission, 2025a; Letta, 2024). These factors have the potential to compromise the EU's capacity to sustain its position as a leader in technology and ensure sustained economic growth. On a global scale, the European Union (EU) is facing challenges to its competitiveness due to geopolitical tensions, fragmentation of global trade, and mounting risks in supply chains. In response to these challenges, the concept of economic security is gaining prominence, emphasizing the need to diversify sources, reducing strategic dependencies, and strengthening the resilience of the European economy (European Commission, 2023). High energy prices in the EU continue to present a substantial challenge, exerting a negative influence on the cost competitiveness of industry, particularly in energy-intensive sectors (European Commission, 2025b; Heussaff, 2024). In addition to external pressures, the EU is confronted with a number of internal structural challenges. The ongoing fragmentation of the single market, the presence of divergent regulatory frameworks, and the imposition of substantial administrative burdens have been shown to increase the costs of conducting business and to impede the cross-border expansion of companies (Borowiecki & Giovannelli, 2025; Letta, 2024). Weaker capital markets and insufficient access to financing for innovative projects further limit the creation and growth of technology-oriented businesses (European Commission, 2025a). A significant challenge confronting the region is the impending demographic shift, characterized by an aging population and a paucity of skilled labor. These factors have the potential to curtail the economic growth prospects of Member States. International institutions have identified the necessity for increased investment in education, skills development, and lifelong learning as a means of promoting productivity and facilitating the adaptation of the workforce to the digital and green transitions (Arnold et al., 2025; European Commission, 2025a). In essence, the EU's competitiveness is contingent upon its capacity to concurrently address global pressures and eliminate internal structural impediments. The European Union's long-term competitiveness is predicated on several key pillars, including the strengthening of innovation capacity, the deepening of the single market, the development of capital markets, and the investment in human capital. Considering the aforementioned challenges, human capital emerges as a pivotal factor in determining the competitiveness of the European Union and its Member States. The quality of the workforce, the level of education, skills, and the ability to adapt to technological change have a significant impact on productivity, innovation performance, and the ability of economies to generate higher added value. A multitude of studies have indicated that investment in education, the cultivation of digital competencies, and the promotion of lifelong learning are indispensable prerequisites for a fruitful transition to a knowledge- and innovation-oriented economy (European Commission, 2025a; Arnold et al., 2025).

Concurrently, evidence suggests that disparities in human capital levels among European Union member states play a pivotal role in the observed disparities in competitiveness. A body of research has demonstrated that countries and regions with a higher concentration of skilled labor, high-quality educational infrastructure, and a developed research and innovation ecosystem achieve better results in terms of productivity, innovation, and overall economic performance (Mulliqi et al., 2018; Žárská & Masárová, 2025). Human capital functions not only as an input factor in production but also as a strategic resource that enables the effective use of new technologies, including artificial intelligence, and strengthens the long-term resilience of the economy (Acemoglu & Autor, 2011; Goldin, 2016).

Despite the extensive literature focused on measuring international competitiveness, only limited attention has been paid to the potential determinants of this competitiveness, especially human capital, particularly in the context of Central and Eastern European economies. In this context, Mulliqi et al. (2018) empirically examine the impact of several human capital indicators

on international competitiveness and formulate key research questions focused on the extent to which the improvement in the competitiveness of Central and Eastern European economies can be explained by the growth of their human capital stocks and whether the differences in performance between countries result from differences in the quality and quantity of this capital.

Human capital is currently regarded as a primary source of economic and organizational wealth, with knowledge and skills applied in practice generating added value becoming a pivotal factor (Gamal, 2008). A plethora of definitions for human capital exists, with various scholars emphasizing education, skills, qualifications, work experience, health, motivation, and investment in individual development (Baron & Armstrong, 2007; Bontis & Fitz-Enz, 2002; Roos et al., 2006). A distinguishing attribute of human capital is its inextricable link to the individual, which significantly impacts economic growth. The quality of human capital is particularly salient, as it influences economic prosperity (Purnomo et al., 2019). The authors also emphasize its accumulative and long-term nature, which contributes to its status as a primary source of sustainable development. In their seminal work, Acemoglu and Autor (2011) propose a definition of human capital as the aggregate of knowledge, information, ideas, expertise, and health possessed by individuals, positing its pivotal role in influencing labor productivity. Building upon this foundation, Goldin (2016) further elaborates on the concept, underscoring its interconnection with investment in education and training, a pivotal factor in the cultivation of human capital. The broader concept also encompasses practical knowledge, acquired skills, and organizational experience, including know-how and organizational memory (Hajšová, 2014; Radenovic & Krstić, 2017). The heterogeneity of approaches to defining human capital is indicative of its intricate nature. This intricacy complicates the accurate measurement of human capital, yet it also facilitates a more profound comprehension of its multidimensional character. Empirical research has confirmed that the value of knowledge, skills, and abilities concentrated in people often exceeds the value of physical capital. These further underscores the strategic importance of human capital for social and economic development (Pravdiuk et al., 2019).

In professional literature, human capital is measured using several types of indicators that capture its quantitative and qualitative dimensions. The most common of these are education-based indicators, utilized in the works of Barro and Lee (2013), the OECD (2023), and the UNDP (2023). These indicators primarily employ the mean years of schooling, expected years of schooling, the proportion of the population with tertiary education, the completion rate of secondary and tertiary education, and the results of international tests (PISA, TIMSS, PIRLS).

Another group consists of studies focusing on skills and competencies (skills-based indicators), which monitor the level of digital skills, problem-solving skills, cognitive abilities (test scores), and participation in lifelong learning (Grundke, 2018; De Grip, 2024; OECD, 2019; PIAAC). A significant focus is placed on health-based indicators, which acknowledge health as a pivotal component of productivity and workforce quality (WHO, 2018; World Bank, 2020). Furthermore, the approximation of human capital is frequently facilitated by the utilization of labor market indicators, including employment by educational attainment, the wages of highly skilled workers, labor productivity, and the proportion of employment opportunities in high-tech sectors. Additionally, innovation indicators, such as the number of researchers, patents, and R&D expenditure, are often employed to approximate human capital.

In recent years, composite indicators have also been widely used, combining several sub-indicators into a single summary index and combining the dimensions of education, health, and income. The most frequently utilized indicators are the Human Development Index (HDI), the Human Capital Index (HCI), the European Human Capital Index (EHCI), and the Education Index. These indices are systematically compiled by international institutions and employed to compare the extent of human capital among nations.

The human capital concept is approximated by the Human Development Index (HDI), a metric that captures key dimensions of education and health. The HDI is a widely used metric in

empirical literature. The HDI is a comprehensive indicator used to assess the level of social and economic development of countries and regions. It captures three basic dimensions of human development: health, education, and income. The index was first introduced by the United Nations Development Programme (UNDP) in the early 1990s and was first published in the Human Development Report in 1990. Human development is conceptualized as a process of expanding individuals' opportunities and enhancing their well-being, which extends beyond narrowly defined economic indicators (Stankovičová & Mojsejová, 2020). In the context of human development, it is imperative to consider not only income levels, but also the development of human capabilities through enhanced health, knowledge, and skills, as well as opportunities to apply individual abilities in working, social, cultural, and political life. In order to comprehensively assess a country's development potential, these areas should be in balance with each other (Majerová, 2012).

The HDI serves as a composite indicator of socio-economic development, evaluating the average results achieved by countries across three dimensions: long and healthy life (health index – HI), access to knowledge (education index – EI), and adequate standard of living (income index – II). The United Nations Development Program (UNDP) employs uniform weights for all three dimensions in its construction, with the resulting Human Development Index (HDI) value determined as the geometric mean of the aforementioned sub-indices (Stankovičová & Mojsejová, 2020).

GOAL AND METHODOLOGY

The primary objective of the study was to examine the relationship between human capital and the competitiveness of economies in Central and Eastern European countries. To this end, the V4 countries were compared with other countries in the region. In addition, the growth dynamics of selected indicators were analyzed, convergence trends were examined, and a regression analysis was performed on the relationship between these indicators in individual countries. The HDI was employed to denote the level of human capital, while the WCI was utilized to indicate the level of competitiveness. The period under analysis was from 2014 to 2023. Due to the unavailability of the HDI, which was last published for 2023, it was not possible to include more recent data. The necessary data were drawn from the United Nations Development Program and the International Institute for Management Development.

Initially, a statistical significance analysis was conducted to ascertain whether there was a substantial discrepancy in the HDI or WCI levels between the V4 countries and other Central and Eastern European nations. To this end, the Mann-Whitney U test was employed, a non-parametric test that, according to Nachar (2008), is among the most robust and capable of yielding statistically significant results. To this end, the Mann-Whitney U test was employed, a non-parametric test that, according to Nachar (2008), is among the most robust and capable of yielding statistically significant results. The analysis was based on the following relationships:

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \qquad (1)$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2 \qquad (2)$$

where:
n1, n2 – sizes of two groups

R1, R2 – sum of the order of values of the first and second groups.

The subsequent section of the analysis examined whether the growth dynamics of human capital in Central and Eastern European countries during the period under review exceeded the

growth dynamics of their competitiveness. To this end, the average growth coefficient was calculated using the geometric mean.

$$x_G = \sqrt[n]{x_1.x_2.\dots x_n} \qquad (3)$$

Subsequent to the analysis of growth dynamics employing the average growth coefficient, the focal point was shifted toward the identification of convergence trends. To this end, the sigma convergence method was employed.

$$(1/ T)* \log (Y_{i,T} / Y_{i,0}) = \alpha + ß * \log Y_{i,0} + U_i \qquad (4)$$

Conversely, a decline in the variance, denoted by σ, within a specified set of countries during the designated period of analysis indicates a convergence of variances among nations (Mazurek, 2013).

In the subsequent phase of the analysis, a simple linear regression analysis was applied separately for each country in order to examine the relationship between the HDI and WCI levels. This methodological approach enabled the assessment of the extent to which changes in HDI can explain the variability in competitiveness levels as expressed by WCI. In order to perform the regression analysis, it was necessary to determine the input data required for substitution into the linear regression function.

$$y_i = b_0 + b_1 x_i + \varepsilon \qquad (5)$$

The Durbin–Watson test was employed to ascertain the reliability of the regression coefficient estimates. The objective of this test is to detect autocorrelation in the residuals and identify potential intertemporal dependencies in the data. As Kenton (2025) asserts, the Durbin–Watson test quantifies the extent of autocorrelation present in the residuals of a regression model. The existence of autocorrelation has the potential to introduce significant distortions into statistical results, thereby leading to incorrect interpretation of trends, a phenomenon that is particularly problematic in the context of time series analysis. The calculations were based on the following relationship:

$$d = \frac{\sum_{t=2}^{T}(e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2} \qquad (6)$$

where:

T - number of observations

e_t - residual (difference between actual and predicted value) for a point in time.

FINDINGS

In the initial phase of the analysis, the focus is on comparing the level of human capital and competitiveness between the V4 countries and other countries belonging to the Central and Eastern European region. The objective of this study is to ascertain the presence of any systematic disparities in the indicators examined between these groups of countries with analogous historical development. To this end, the Mann–Whitney U test is employed, which first analyzes the level of human capital expressed by the HDI index and then the level of competitiveness expressed by the WCI index. The research question guiding this study was as follows: Do the V4 countries exhibit a distinct level of human capital, as measured by the HDI, when compared to other countries within the Central and Eastern European region?

H0: There is no statistically significant difference in HDI between the V4 countries and other countries in the Central and Eastern European region.

H1: There is a statistically significant difference in HDI between the V4 countries and other countries in the Central and Eastern European region.

Table 1: Mann-Whitney U test: HDI

Group 1	Group 2	U value	Critical value u (p <0,05)	Z-score	p- value	Statistical significance
V4 Countries	The remaining states falling within the region of Central and Eastern Europe	55	31	-0.03413	0.48803	no

Source: UNDP, own calculations

The objective was to ascertain whether there is a statistically significant disparity in HDI between the V4 countries and other countries in the Central and Eastern European region. The period under analysis spanned from 2014 to 2023. The empirical distribution function of the test statistic U was determined to be 55, whereas the critical value at a significance level of $\alpha = 0.05$ was 31. Given that the calculated U value exceeds the critical value, the null hypothesis (H0) was accepted. This hypothesis posits that there is no statistically significant difference in HDI between the V4 countries and other countries in the Central and Eastern European region. This finding was corroborated by the low Z-score of 0.03413, which signifies a negligible disparity between the compared groups of countries, as well as the relatively high p-value of $0.48803 > 0.05$. The findings indicate that disparities in the aggregate level of human capital within the Central and Eastern European region are less pronounced than would be anticipated based on discrepancies in economic performance or the extent of integration into European structures.

Following an examination of the level of human capital expressed by the HDI index between the two groups of countries, a comparison of their competitiveness as expressed by the WCI index is subsequently undertaken. The research question guiding this study was as follows: Do the V4 countries exhibit a distinct level of competitiveness, as measured by the WCI, when compared to other countries within the Central and Eastern European region?

H0: There is no statistically significant difference in WCI between the V4 countries and other countries in the Central and Eastern European region.

H1: There is a statistically significant difference in WCI between the V4 countries and other countries in the Central and Eastern European region.

Table 2: Mann-Whitney U test: WCI

Group 1	Group 2	U value	Critical value u (p <0,05)	Z-score	p- value	Statistical significance
V4 Countries	The remaining states falling within the region of Central and Eastern Europe	49	31	-0.44364	0.32997	no

Source: IMD, own calculations

As in the previous case, the Mann-Whitney U test was used to determine whether there was a statistically significant difference in WCI values between the V4 countries and other countries in the Central and Eastern European region. The analysis was conducted on data from 2014 to 2023, with a significance level of $\alpha = 0.05$. The test statistic U was found to be 49, whereas the critical value at $p < 0.05$ is 31. Given the statistical insignificance of the WCI disparity between the V4 countries and those in Southeast and Eastern Europe, as evidenced by $U = 49 > 31$, it can be concluded that the observed differences in WCI are not statistically significant. This finding was corroborated by the low z-score of -0.44364, which falls within the insignificance interval, and by the relatively high p-value of 0.32997. The findings of this study support hypothesis H0, which posits that there is no statistically significant difference in WCI between the V4 countries and the other countries in Central and Eastern Europe. This finding suggests that, in terms of the development of competitiveness and the factors that may influence it, the V4 countries do not differ significantly from other countries in the region under review. This may be the result of their similar historical and institutional development.

A statistical analysis reveals no significant disparities between the V4 countries and other Central and Eastern European countries with regard to human capital or overall competitiveness. This phenomenon can be attributed to the composition of the two groups of countries, which include nations with relatively high and low values for individual indicators. For instance, within the WCI framework, countries such as the Czech Republic and Estonia demonstrate higher values, while Croatia, Bulgaria, and Slovakia, for instance, exhibit lower values. In the HDI, Slovenia, the Czech Republic, and Estonia exhibit higher values, while Romania, Bulgaria, and Hungary demonstrate lower values.

As human capital is frequently regarded as a primary factor contributing to enhanced economic performance and competitiveness in individual countries, subsequent analyses will concentrate on ascertaining whether the growth of human capital in Central and Eastern European countries during the specified period surpassed the growth of competitiveness in those countries. The average growth coefficient was employed to facilitate a comparative analysis of the dynamics exhibited by both indicators, thereby enabling a systematic comparison of the rate of change in HDI and WCI.

Table 3: Average growth coefficient - WCI

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Geomean
Bulgaria	-	1.099	1.227	1.065	0.999	0.939	0.964	0.855	1.011	0.912	1.003
Czechia	-	1.139	1.075	1.037	1.007	0.924	0.970	0.947	1.124	1.101	1.033
Estonia	-	1.075	1.063	1.057	1.009	0.926	1.049	0.968	1.071	0.973	1.020
Croatia	-	1.148	1.153	1.096	0.979	0.918	0.864	0.982	1.329	0.959	1.039
Latvia	-	0.967	1.113	1.080	1.006	0.952	0.921	1.012	1.035	0.824	0.986
Lithuania	-	1.157	1.032	1.021	1.017	0.991	0.786	1.172	1.045	0.976	1.016
Hungary	-	1.086	1.099	1.028	1.024	0.963	1.158	0.838	1.068	0.908	1.015
Poland	-	1.113	1.037	1.034	1.023	0.943	0.941	0.824	0.967	1.133	0.998
Romania	-	1.081	1.090	1.040	1.003	0.932	0.918	0.984	0.973	1.040	1.005
Slovenia	-	1.227	1.143	1.091	1.037	0.973	0.962	0.922	1.043	0.952	1.035
Slovakia	-	1.073	1.152	0.982	0.928	0.958	0.861	1.060	1.019	1.006	1.001

Source: IMD, own calculations

The average WCI growth coefficient, expressed as a geometric mean, captures the WCI trend between 2014 and 2023. The findings indicate that in nine out of eleven countries, there was a slight increase in the WCI during the period under review, despite the fact that the WCI

alternately decreased and increased in most countries. The highest average growth coefficient was recorded in Croatia (1.039), where the WCI increased by 3.9% during the period under review. Conversely, the lowest coefficient, indicating a decline, was recorded in Latvia (0.986). A decline was also documented in Poland, albeit to a lesser extent (0.998). This decline is distinct from the one observed in Latvia. Consequently, it can be deduced that the disparities in WCI dynamics among the countries examined are not substantial, with the majority exhibiting only moderate growth or stagnation. This finding suggests that the WCI level in these countries is subject to only minor fluctuations, exhibiting average growth or decline over the 10-year period.

Table 4: Average growth coefficient - HDI

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Geomean
Bulgaria	-	1.006	1.004	1.002	1.004	1.004	0.989	0.989	1.022	1.012	1.003
Czechia	-	1.002	1.002	1.002	0.997	1.002	0.994	1.003	1.011	1.004	1.002
Estonia	-	1.003	1.002	1.004	1.003	1.004	1.000	0.998	1.003	1.003	1.002
Croatia	-	1.005	1.005	1.007	1.006	1.006	0.994	1.010	1.011	1.003	1.005
Latvia	-	1.006	1.006	1.007	1.006	1.006	0.999	0.991	1.011	1.009	1.004
Lithuania	-	1.003	1.007	1.011	1.005	1.006	0.993	0.999	1.001	1.008	1.004
Hungary	-	0.999	1.005	1.002	1.005	1.005	0.995	0.994	1.018	1.003	1.003
Poland	-	1.007	1.006	0.998	1.002	1.003	0.992	1.005	1.020	1.004	1.004
Romania	-	1.004	1.000	1.006	1.006	1.006	0.993	0.996	1.013	1.006	1.003
Slovenia	-	1.002	1.006	1.004	1.004	1.001	0.995	1.007	1.002	1.005	1.003
Slovakia	-	1.002	1.003	1.001	1.003	1.003	0.995	0.991	1.016	1.008	1.003

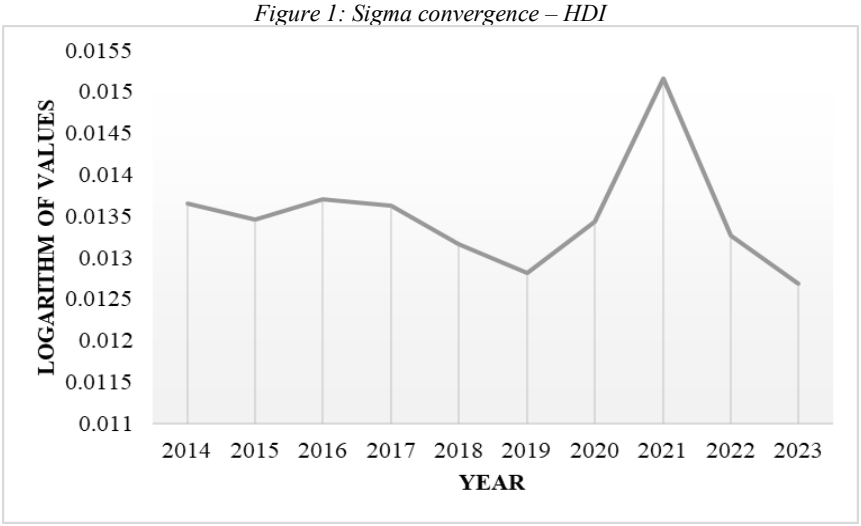
Source: UNDP, own calculations

The average growth rate of the Human Development Index, expressed as a geometric mean for the period 2014 to 2023, demonstrates a slight yet persistent increase in all countries under observation. The growth rate values range between 1.002 and 1.005, indicating that during the period under review, the HDI increased by 0.2% to 0.5%. The largest increase was observed in Croatia, while the smallest was recorded in the Czech Republic and Estonia. Notably, these countries are among the leaders in the Central and Eastern European region.

A comparative analysis of the average growth rate from 2014 to 2023 reveals that the growth dynamics of human capital surpassed those of competitiveness in four of the eleven countries under observation: Bulgaria by 0.1%, Latvia by 1.8%, Poland by 0.6%, and Slovakia by 0.2%. In the remaining seven countries, competitiveness growth exhibited an increase that exceeded human capital growth. The following countries have shown the following percentages: the Czech Republic (3.1%), Estonia (1.7%), Croatia (3.4%), Lithuania (1.3%), Hungary (1.2%), Romania (0.2%), and Slovenia (3.2%).

Subsequent to the evaluation of growth dynamics employing the average growth coefficient, the focus then transitions to the analysis of convergence trends. While the average growth coefficient provides insight into the direction and intensity of growth, σ-convergence offers a more nuanced perspective by incorporating variability between countries. This variability indicates whether countries within a region are converging towards a shared level of the indicators examined or, conversely, whether the observed differences between them are increasing.

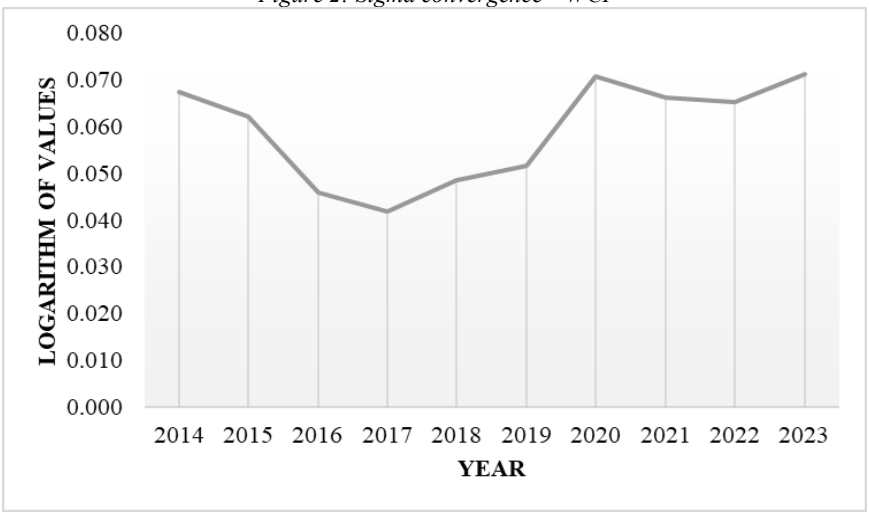
Figure 1: Sigma convergence – HDI



Source: UNDP, own elaboration

The development of the standard deviation of HDI values among Central and Eastern European countries in the period 2014 to 2023 points to a relatively stable level of differences in human capital within the region. During the observed period, the standard deviation values fluctuated within a narrow range from 0.0127 to 0.0152. A decline in standard deviation, indicative of a gradual convergence in HDI, is evident from the inception of the observed period. However, this trend was not sustained. In the 2020-2021 period, there was an increase in the standard deviation. This increase may be related to the impact of the Coronavirus disease 2019 (Covid-19) pandemic on individual countries, particularly in the areas of health and education, which are key components of the Human Development Index (HDI). In the 2022-2023 period, the standard deviation exhibited a decline, suggesting a tendency towards convergence at the conclusion of the period under consideration. These findings in the area of human capital development are thus consistent with previous findings that there are no statistically significant differences in HDI levels between the V4 countries and other countries in the Central and Eastern European region.

Figure 2: Sigma convergence – WCI



Source: IMD, own calculations

The standard deviation values of WCI ranged from 0.042 to 0.071, indicating that there are more significant differences between countries in terms of competitiveness than in terms of human capital. From the inception of the period under review, a slight decline in standard deviation can be observed, as evidenced by the HDI. Subsequently, between 2018 and 2020, there was an increase and subsequent stagnation in the following period. In consideration of the aforementioned developments, it is not feasible to identify a discernible convergence or divergence trend. Consequently, the disparities in competitiveness between nations remained relatively stable during the period under

examination. In this case, the findings are consistent with previous results, which indicate that there are no statistically significant differences in the WCI index between the V4 countries and other Central and Eastern European countries.

In the subsequent section, regression analysis is applied separately for each country to examine the relationship between the level of human capital and the level of competitiveness. Subsequently, the Durbin-Watson test was employed to assess the autocorrelation of the residuals, thereby substantiating the reliability of the estimates of the regression coefficients for each nation.

Table 5: Regression analysis — Bulgaria

Country	β (coefficient HDI)	Intercept	R^2	Adjusted r^2	t-stat β	p-value β	Durbin-Watson
Bulgaria	95.78	–23.46	0.0106	–0.113	0.293	0.777	0.505

Source: UNDP, IMD, own calculations

The application of regression analysis to data concerning Bulgaria indicates that HDI growth exerts a positive effect on WCI, albeit one that is statistically insignificant. This conclusion is supported by a high p-value (0.777). The value of the coefficient of determination, R^2, is 0.011, indicating that HDI accounts for a mere 1% of the variability in competitiveness. The Durbin-Watson test value (0.505) indicates positive autocorrelation of residuals, suggesting that intertemporal dependencies are not captured in the model. Therefore, the results should be interpreted with caution. The findings indicate that human capital growth in Bulgaria does not exert a substantial influence on enhancing competitiveness.

Table 6: Regression analysis – Czech Republic

Country	β (coefficient HDI)	Intercept	R^2	Adjusted r^2	t-stat β	p- value β	Durbin-Watson
Czechia	780.92	-631.5	0.478	0.413	2.706	0.027	1.05

Source: UNDP, IMD, own calculations

The application of regression analysis within the Czech Republic demonstrates that HDI growth exhibits a statistically significant positive impact ($\beta = 780.93$) on WCI, a finding that is substantiated by a p-value of $0.027 < 0.05$. The coefficient of determination of 0.478 indicates that nearly 48% of the total variability in competitiveness is attributable to changes in human capital. However, given the relatively low value of R^2, it must be acknowledged that, in addition to human capital, other factors not examined in this study must also influence competitiveness in the Czech Republic. The Durbin-Watson test yielded a value of 1.05, indicating a slight positive autocorrelation of residuals. While this value is lower, it does not preclude the interpretation of the results. Consequently, it can be posited that, in contrast to Bulgaria, an increase in HDI directly contributes to the enhancement of competitiveness in the Czech Republic.

Table 7: Regression analysis – Estonia

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Estonia	504.72	-378.15	0.541	0.483	3.07	0.015	1.5

Source: UNDP, IMD, own calculations

The findings of the regression analysis in Estonia demonstrate a positive and significant relationship between the growth of human capital, as measured by HDI, and the development of competitiveness, as expressed by WCI. This indicates that an increase in human capital is associated with an enhancement in competitiveness. The value of the coefficient of determination, $R^2 = 0.541$, indicates that HDI accounts for more than 54% of the total variability, which is higher than in the Czech Republic. The Durbin-Watson test yielded a value of 1.5, indicating a slight positive autocorrelation of residuals. This value does not significantly call into question the validity of the regression analysis.

Table 8: Regression analysis – Croatia

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Croatia	255.1	-171.58	0.284	0.195	1.783	0.112	1.07

Source: UNDP, IMD, own calculations

Regarding Croatia, regression analysis reveals a positive correlation between human capital growth and competitiveness development. This correlation is substantiated by the positive estimate of the regression coefficient, β. However, it cannot be considered statistically significant, as the p-value of 0.112 is greater than $\alpha = 0.05$. The value of the coefficient of determination, $R^2 = 0.284$, indicates that approximately 28% of the variability in WCI is explained by changes in HDI. This finding suggests that the model's explanatory power is limited and indicates the necessity of considering additional factors that influence the development of WCI. The Durbin-Watson test yielded a value of 1.07 in this case, indicating a slight positive autocorrelation of the residuals. Consequently, the results of the regression analysis must be interpreted with a degree of caution. Therefore, although there is a suggestion of a positive relationship between the indicators examined in Croatia, it cannot be regarded as sufficiently robust and consistent.

Table 9: Regression analysis – Latvia

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Latvia	-21.096	83.37	0.002	-0.123	-0.119	0.908	0.99

Source: UNDP, IMD, own calculations

In the case of Latvia, the regression coefficient β, which has a value of 21.10, indicates only a very weak negative relationship between human capital, measured by HDI, and competitiveness development, measured by WCI. This relationship cannot be considered statistically significant based on the p-value of 0.908. The remarkably low value of $R^2 = 0.002$ suggests that changes in HDI account for a mere 0.2% of the variability in WCI, indicating that human capital exerted minimal influence on the shift in Latvia's competitiveness level during the observed period The insignificance of the results was corroborated by the Durbin-Watson test, which yielded a value of 0.99, thereby indicating positive autocorrelation of residuals. This finding suggests that the enhancement of Latvia's competitiveness is likely to be influenced by factors other than the mere increase in human capital.

Table 10: Regression analysis – Lithuania

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Lithuania	197.88	83.37	0.119	0.008	1.038	0.33	1.67

Source: UNDP, IMD, own calculations

In Lithuania, a positive relationship was observed between human capital growth, measured by the HDI, and competitiveness development, expressed by the WCI. However, given that the p-value of 0.33 exceeds the critical value of $\alpha = 0.05$, the result cannot be considered statistically significant. The coefficient of determination indicates that less than 12% of the variability in the WCI is attributable to changes in the HDI, suggesting that the model exhibits a relatively low degree of explanatory power. However, the Durbin-Watson test yielded a value of 1.67, suggesting a slight positive autocorrelation of the residuals. This outcome can be regarded as satisfactory. However, in the case of Lithuania, it can be posited that the growth of human capital is reflected only weakly and inconsistently in an increase in competitiveness. Therefore, other factors not captured in this analysis must have a more significant impact on its formation.

Table 11: Regression analysis – Hungary

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Maďarsko	270.36	-168.8	0.136	0.028	1.123	0.294	1.36

Source: UNDP, IMD, own calculations

The findings of the regression analysis for Hungary indicate a positive relationship between human capital growth and competitiveness development. This is substantiated by the estimated regression coefficient, β, which is positive (270.36). However, the p-value of $0.294 > \alpha = 0.05$ indicates that this relationship is not significant. Therefore, it cannot be concluded that the increase in HDI had a clear impact on the increase in WCI during the period under review. The insignificance of the results is also confirmed by the low coefficient of determination R^2, which shows that the model explains only 13.6% of the total variability. Consequently, factors beyond the level of human capital must exert an impact on the growth of competitiveness in Hungary.

Table 12: Regression analysis – Poland

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Poland	-336.43	363.93	0.198	0.098	-1.406	0.197	0.84

Source: UNDP, IMD, own calculations

In Poland, regression analysis revealed a negative correlation between human capital development and economic competitiveness. This finding defies conventional assumptions regarding the expected positive correlation between these indicators. However, in Poland, an increase in HDI was associated with a decline in WCI during the period under review. However, this relationship did not prove to be statistically significant, as evidenced by the p-value ($0.197 > \alpha = 0.05$). The model's explanatory power was found to be inadequate, as evidenced by the relatively low coefficient of determination ($R^2 = 0.198$). The Durbin–Watson test yielded a value of 0.84, indicating significant positive autocorrelation of residuals. This finding suggests that the reliability of estimates is reduced, likely due to the fact that simple linear regression is incapable of capturing the fluctuating development of the WCI.

Table 13: Regression analysis – Romania

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Romania	-60.3	108.23	0.011	-0.112	-0.301	0.771	0.56

Source: UNDP, IMD, own calculations

The regression analysis results in Romania demonstrated a modest negative correlation between HDI and WCI. However, this correlation did not attain statistical significance, as indicated by a p-value of 0.771, which exceeded the alpha level of 0.05. This finding was corroborated by the coefficient of determination R^2, which indicated that the model accounted for a mere 1.1% of the variability in WCI, suggesting a negligible explanatory capacity. The Durbin–Watson statistic in this case demonstrated a value of 0.56, indicating a robust positive autocorrelation of residuals. This finding indicates that the development of competitiveness in Romania is characterized by a substantial dynamic component that is not fully captured by the model. Consequently, this dynamic component leads to a reduction in the reliability of the estimated parameters.

Table 14: Regression analysis – Slovenia

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p- value β	Durbin-Watson
Slovenia	627.33	-512.25	0.348	0.266	2.066	0.073	0.67

Source: UNDP, IMD, own calculations

A regression analysis of Slovenia indicated a moderately strong positive relationship between the Human Development Index (HDI) and economic competitiveness. Pursuant to the regression coefficient value $\beta = 627.33$, it can be posited that human capital growth in this nation is concomitant with heightened competitiveness. However, the p-value for the regression coefficient 0.073 slightly exceeded the statistical significance level $\alpha = 0.05$. The coefficient of determination $R^2 = 0.348$ indicated that approximately 35% of the variability in WCI can be attributed to changes in HDI, which is a higher value compared to most of the countries examined. However, this does not guarantee that the model possesses sufficient explanatory power. This hypothesis was corroborated by the outcomes of the Durbin–Watson test (0.67), which indicated that the temporal dynamics underlying the development of competitiveness are not fully reflected in the model. Consequently, the interpretation of the results should be conducted with a high degree of caution.

Table 15: Regression analysis – Slovakia

Country	β (coefficient HDI)	Intercept	R^2	Adjusted R^2	t-stat β	p-value β	Durbin-Watson
Slovakia	-88.048	133.12	0.012	-0.112	-0.31	0.764	0.79

Source: UNDP, IMD, own calculations

In the Slovak context, as in the broader international sample, no statistically significant relationship between HDI and WCI was confirmed in the period 2014-2023. This finding is supported by the p-value for the regression coefficient (0.764) exceeding the alpha level of 0.05. The value of the coefficient of determination, $R^2 = 0.012$, indicates that the model accounts for a mere 1.2% of the variability in competitiveness, deeming it to possess negligible informative value. Consequently, human capital does not serve as the primary factor that determines the level of competitiveness in Slovakia. This hypothesis was supported by the Durbin–Watson test value of 0.74, which indicates positive autocorrelation of residuals. That is, the model does not effectively capture the relationship under investigation.

The findings of a simple regression analysis in eleven countries in Central and Eastern Europe predominantly suggest an insignificant impact of human capital on the competitiveness of economies, despite the anticipated contrary outcome. A statistically significant impact of HDI on WCI was recorded in the Czech Republic and Estonia; however, the explanatory power of the models was not particularly high in these countries either. However, the Durbin–Watson test indicated a slight positive autocorrelation of residuals in these countries, which does not preclude the interpretation of the results. These countries thus represent an exception within the region under review, where it has been demonstrated that human capital growth does indeed contribute to

increased competitiveness. The insignificance or ambiguity of the impact of human capital on the level of competitiveness in the remaining nine states can be explained by several factors. Of these, the most salient is the uneven development of the WCI, which exhibits frequent year-on-year fluctuations. A multitude of additional factors that have the capacity to exert a substantial influence on the development of competitiveness are incorporated into the WCI calculation. These factors may not have demonstrated positive development during the period under review. Such factors include, but are not limited to, investment in infrastructure, innovation activities, and structural reforms. In the period under review, developments may have been influenced by external shocks, including the impact of the Coronavirus Disease 2019 (Covid-19) pandemic. The effects of the pandemic were reflected in the sigma convergence achieved.

DISCUSSION

A comparative analysis of Central and Eastern European countries reveals that they exhibit similar levels of competitiveness to those observed in the most developed EU countries. This finding aligns with the conclusions of Tijanic and Obadic (2015), who reported that the majority of new EU member states demonstrate lower levels of competitiveness in comparison to their predecessors. This phenomenon can be attributed to the observation that countries that acceded to the EU later allocate a greater proportion of their investment budgets to infrastructure and environmental initiatives as opposed to human capital development. Miron et al. (2022) emphasize the role of human capital as a strategic element of competitiveness in strengthening the process by which lagging countries catch up with advanced countries. However, a comparative analysis of the average growth rate of human capital and competitiveness in the countries under scrutiny revealed that in seven of the eleven countries (the Czech Republic, Estonia, Croatia, Lithuania, Hungary, Romania, and Slovenia), the increase in competitiveness exhibited greater dynamism than the increase in human capital. However, Sener & Delican (2019) have indicated that the promotion of competitiveness in less developed countries is more challenging than in the most developed countries and requires different mechanisms, which may be the reason for this situation. The convergence method did not reveal any clear convergence or divergence trends between countries. However, a tendency towards divergence was observed during the pandemic, which may reflect the sensitivity of HDI and WCI developments to external shocks, as well as the different approaches taken by countries to managing the impact of the pandemic. Preliminary regression analysis indicated that, across nine of the eleven Central and Eastern European countries examined, human capital exhibited no substantial influence on competitiveness. This finding contradicts Onyusheva's (2017) observation that factors influencing human capital are correlated with the level of economic competitiveness in the Republic of Kazakhstan. In the region under examination, a statistically significant impact of human capital on competitiveness was confirmed only in the Czech Republic and Estonia. However, given the relatively lower values of the coefficient of determination, it can be concluded that other factors must also have a major impact on competitiveness in these two countries. For instance, Ábel et al. (2025) underscore the significance of innovation and technological advancement in this context. The findings of the Durbin-Watson test indicated that simple linear models may not adequately capture the development of competitiveness. This is because competitiveness is typically attributed to the combined influence of multiple factors rather than to the effect of a single factor alone (Schwab and WEF, 2015). Furthermore, Hanushek & Woessmann (2012) emphasize that the impact of human capital may not be direct, but rather indirect, manifesting through innovation or productivity.

While we have succeeded in highlighting certain salient facts, it is imperative to acknowledge the limitations inherent in the examination of the relationship between human development and the competitiveness of nations. Firstly, it is imperative to acknowledge that competitiveness is a multidimensional concept, which precludes its full capture by a single indicator. The World Competitiveness Index (WCI) is a comprehensive metric of economic

performance and institutional environment, though it is subject to certain limitations. The index is based on a combination of hard statistical data and questionnaire survey results, which may affect its objectivity and international comparability to some extent. As Olczyk (2016) observes, the selection of variables, the weighting of components, and the integration of hard and subjective data can result in methodological ambiguity and challenges regarding the objectivity of the resulting competitiveness rankings. Secondly, the Human Development Index (HDI) is also an aggregate indicator that captures the fundamental dimensions of human development. However, it does not fully reflect the quality of education, the structure of the workforce's skills, or the specific competencies relevant to the digital and knowledge economy. Consequently, the HDI may underestimate certain aspects of human capital that are critical to competitiveness. Therefore, Herre & Arriagada (2023) recommend considering the use of other indices, such as the Inequality-Adjusted Human Development Index (IHDI), the Gender Development Index (GDI), or the Augmented Human Development Index (AHDI). Thirdly, a temporal discrepancy exists between alterations in human development and their subsequent impact on competitiveness. Consequently, short-term fluctuations in the HDI value may not directly correspond to changes in the WCI level, thereby complicating the interpretation of the results. It is important to note that the results may be influenced by factors not directly included in the model. These factors may include institutional quality, economic policy, economic structure, or external shocks (e.g., financial crises, pandemics, or geopolitical events). Therefore, it is imperative that the findings be interpreted with appropriate caution.

CONCLUSION

The objective of the present study was to examine the relationship between human capital and the competitiveness of economies in Central and Eastern European countries. To this end, a comparative analysis was conducted among the V4 countries and other countries in the region. The study further involved an analysis of the growth dynamics of selected indicators, an examination of convergence trends, and a regression analysis of the relationship between these indicators in individual countries. This objective was successfully achieved. The results of the Mann–Whitney U test demonstrated that there were no statistically significant differences in the level of human capital or competitiveness between the V4 countries and the other countries in the Central and Eastern European region. This finding suggests that all countries exhibit analogous indicator values. This phenomenon may be attributed to the historical developments that characterized the second half of the 20th century, during which all countries operated within centrally planned, socialist-oriented economies. An analysis of the dynamics of human capital and competitiveness development demonstrated that the HDI exhibited positive growth in all the countries examined; however, the increases between 2014 and 2023 were negligible. The development of the WCI exhibited less stability, with regular fluctuations occurring within individual years. In the case of Latvia and Poland, a decline was observed during the period under review. The σ-convergence results complemented the previous analysis by offering a perspective on the development of differences between countries. However, in neither scenario can a stable convergence or divergence trend be identified. The standard deviation for both the HDI and the WCI exhibited an alternating pattern between decline and increase. For instance, an inclination toward divergence was noted during the CoV-19 pandemic, a phenomenon that may be indicative of the sensitivity of these indicators to external shocks. The application of regression analysis revealed that, in nine out of 11 countries, human capital exhibited no significant impact on competitiveness. The correlation observed in these nations was either negligible or non-existent, particularly in the case of Poland, indicating that competitiveness might be contingent on disparate factors. The statistical significance of human capital on competitiveness was confirmed in the Czech Republic and Estonia. However, even within these countries, the model explained only about 50% of the total variability. Furthermore, the outcomes of the Durbin–Watson test indicated the presence of relatively significant autocorrelation of residuals in several instances, suggesting the dynamic nature of competitiveness development, which simple linear models are incapable of fully capturing.

Considering the findings, it can be posited that human capital, while widely regarded as a pivotal catalyst for sustained economic growth and an instrumental factor in enhancing competitiveness, does not invariably translate into tangible gains in competitiveness within the context of Central and Eastern European countries. The analysis indicates that, in the absence of other concomitant factors, the mere augmentation of human capital is insufficient to trigger a substantial escalation in competitiveness. These findings underscore the necessity for a more comprehensive approach to enhancing the competitiveness of economies in the region of Central and Eastern Europe.

The social contribution of this study lies primarily in public policy-making aimed at supporting competitiveness and long-term development in Central and Eastern European countries. The finding that the growth of human capital in the region alone is not sufficient to significantly increase competitiveness indicates the necessity for a more comprehensive and integrated approach to economic policy that extends beyond traditional investments in education and health. The social contribution of the work is twofold. Firstly, it provides empirical evidence that can be used by national and regional development strategy makers. This evidence can be used to allocate public resources in a more targeted manner and focus on areas with the highest multiplier effect. Consequently, the research endeavors can contribute to the reduction of regional inequalities, the promotion of social inclusion, and the enhancement of the quality of life of the population in the Central and Eastern European region. From a methodological perspective, the study underscores the efficacy of integrating non-parametric tests, growth dynamics analysis, convergence methods, and regression analysis in the examination of intricate macroeconomic relationships. This approach can function as a foundational starting point for subsequent research endeavors focused on other regions or for extending the model with additional variables. In sum, the work contributes to a more profound comprehension of the conditions under which human capital can support competitiveness. Furthermore, it establishes a foundation for future research aimed at identifying the factors that strengthen or weaken this relationship.

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EXPLORING THE STRATEGIC POTENTIAL OF AGE MANAGEMENT FOR WORKFORCE SUSTAINABILITY: A SYSTEMATIC LITERATURE REVIEW

Simona KOSÁKOVÁ

Abstract

Research background: Population ageing and demographic changes are significantly transforming labor markets and creating new challenges for organizations in maintaining a sustainable workforce. As the proportion of older employees increases, organizations must adopt strategies that enable employees to remain productive, healthy, and engaged throughout their working lives. In this context, the concept of age management has gained increasing attention in both academic research and organizational practice. Age management encompasses a set of organizational policies and practices aimed at effectively managing age diversity, supporting longer working lives, and improving the well-being and performance of employees across different age groups. Previous studies have examined various aspects of age management, including health promotion, lifelong learning, flexible work arrangements, and knowledge transfer. However, despite the growing body of research on this topic, there is still a lack of a systematic literature review that synthesizes existing knowledge and identifies key research directions.
Purpose of the article: The aim of this study is to systematically review the existing literature on age management and to explore its strategic potential for workforce sustainability. Specifically, the study seeks to identify the main research trends, thematic areas, and approaches discussed in the academic literature. Furthermore, the review aims to highlight research gaps and underexplored areas that may guide future research in the field of age management and sustainable workforce development.
Methods: This study applies a systematic literature review following the PRISMA guidelines to ensure a transparent and structured selection of relevant academic publications. Relevant studies were identified through database searches and subsequently screened based on predefined inclusion and exclusion criteria. After the selection process, the final set of articles was analyzed to identify major research themes and patterns. In addition, a qualitative synthesis of the literature was conducted to examine how age management is addressed in relation to workforce sustainability and to highlight the dominant perspectives within the existing research.

Key words: *age management, older workers, workforce sustainability, sustainable employability, lifelong learning*

JEL Classification J11, J24, J26 https://doi.org/10.52665/ser20260104

INTRODUCTION

Population ageing represents a fundamental challenge for the sustainability of labour markets and pension systems. A declining birth rate, together with increasing life expectancy, is leading to a reduction in the proportion of the economically active population. This demographic shift creates growing pressure to extend working lives and adapt labour market structures (Vyhlídal; Aitken & Singh; Novak et al.). Cross-country analyses indicate that the likelihood of remaining in employment beyond the age of 60 is significantly influenced by health status, socio-economic position, and the level of education. These factors play a crucial role in shaping individuals' capacity and willingness to continue working in later life. (Head et al., 2024; Lu et al., 2023; Macken et al., 2022). However, the risk of early exit from the labour market is not evenly distributed across the population. It varies significantly depending on individual characteristics and socio-economic conditions (Oylu et al., 2025). Studies have identified a lower likelihood of re-employment at older ages, with older workers more frequently facing the risk of occupational downgrading following periods of unemployment. (Brydsten et al., 2023) Research has highlighted

the existence of differentiated retirement trajectories that reflect underlying social inequalities and individuals' economic conditions.

At the same time, health status and working conditions play a significant role in shaping decisions to remain in employment. Authors (Petersen et al., 2025) emphasize the role of physical capacity and supportive working environments in extending working life, while (Abrams et al., 2025) highlight the negative impact of unstable work schedules on the well-being of older workers. (Nivalainen, 2022) confirms that health status and job control are key determinants of both planned and actual retirement age. In response to these challenges, the concept of age management has gained increasing attention as a strategic approach to managing age diversity within organizations. (Urbancova et al., 2020) provide empirical evidence that the systematic implementation of age management practices can contribute to competitive advantage and workforce stability. In contrast, (Vrabcova & Urbancova, 2022) highlight that during periods of crisis, the systematic management of older workers tends to weaken. Despite the extensive research on individual determinants, the literature remains fragmented and offers only limited integration of macroeconomic, organizational, and individual factors related to workforce sustainability. Therefore, this study aims to systematize existing knowledge and identify the mechanisms through which age management can support long-term labour market participation.

LITERATURE OVERVIEW

The literature suggests that one of the key mechanisms supporting workforce sustainability is lifelong learning and the systematic development of older workers' competencies. (Naegele et al., 2025) highlight unequal access to vocational training and emphasize that internalized age-related stereotypes may negatively affect older workers' motivation to participate in training activities. Building on these findings, (Li et al., 2023), provide empirical evidence that participation in education significantly increases the intention to remain in employment beyond retirement eligibility, particularly when organizations foster an age-inclusive climate and actively support the development of older employees. An important factor in the development of employability is also intergenerational interaction and knowledge sharing. (Chen et al., 2025) confirm that intergenerational interactions and reciprocal knowledge transfer enhance the self-perceived employability of older workers, with a positive intergenerational climate further strengthening this effect. (Lagace et al., 2023) additionally demonstrate that systematic knowledge-sharing practices reduce age-related stereotypes while increasing work engagement and the intention to remain within the organization. (Marcaletti et al., 2023) further suggest that the positive effects of training are particularly evident among workers aged 50 and over, where they help mitigate the negative impact of long-term seniority on job quality. In the context of technological change, the development of digital competencies has become increasingly important. (Low et al., 2025) emphasize that lifelong learning and the development of artificial intelligence–related skills enhance the career resilience of older workers. Similarly, (Xie et al., 2023) identify access to digital training as a key factor supporting autonomy and competence self-efficacy, which in turn increases the intention to remain in employment. Education thus represents not only a tool for adapting to technological change but also a mechanism for stabilizing labour market participation in later career stages.

However, workforce sustainability is not determined solely by the development of competencies, but also by employer perceptions and organizational culture. (Lee et al., 2026) identify differing recruitment preferences toward "mature" and "senior" workers, with assessments of their adaptability and competencies significantly influencing hiring decisions. (Meng et al., 2022) confirm that negative managerial attitudes and experiences of age discrimination increase the risk of job loss prior to reaching retirement age. Conversely, (Binyamin & Brender-Ilan, 2023) highlight the importance of communication climate and the social environment in shaping attitudes

toward middle-aged workers, showing that a positive organizational communication setting can mitigate discriminatory tendencies. (Jensen et al., 2024) find that age-related stereotypes do not necessarily translate into discriminatory HR practices, pointing to the important role of broader institutional and cultural contexts.

The concept of sustainable employability provides a broader framework for understanding these processes. (Neupane et al., 2022) define sustainable employability as a multidimensional construct encompassing health, well-being, and competencies, while also pointing to the relative stability of these indicators over time. However, (Verdonk et al., 2022) critically argue that existing definitions often fail to adequately reflect a life-course perspective and the diversity of career trajectories, thereby limiting their ability to capture the complexity of later career stages. The heterogeneity of career trajectories is further illustrated by research focusing on so-called "bridge employment". (Mazumdar et al., 2023) highlight that older workers sometimes deliberately choose non-standard forms of employment, where the extent to which employer expectations are fulfilled significantly influences their work attitudes and intention to remain employed. (Hallpike et al., 2024) identify both individual and contextual strategies through which career sustainability can be optimized in later career stages, emphasizing the importance of multi-actor involvement in career decision-making processes. Furthermore (Sousa-Ribeiro et al., 2025) underline the role of organizational support, well-being, and perceived competence in post-retirement employment. In a related vein, (Aisa et al., 2023) link technological change, skills development, and delayed retirement, highlighting the growing importance of continuous upskilling in the context of automation. The importance of career sustainability in the context of an ageing workforce is emphasized by (van der Heijden & Vermeeren, 2025), who demonstrate that the ability and willingness to work until retirement age result from the interaction between individual resources and organizational support. Their findings suggest that workforce sustainability cannot be reduced solely to health status or chronological age but should instead be understood as a dynamic process unfolding across the entire working life. The conceptual linkage between ageing and career sustainability is further developed by (Visentini et al., 2025), who identify key dimensions of professional longevity and successful ageing. This framework allows age management to be understood not merely as an HR tool, but as a broader strategic approach aimed at supporting long-term labour market participation. From an organizational perspective, (Lima & de Amorim, 2025) show that organizations that systematically invest in HR policies and diversity management are better positioned to attract and retain older workers. This implies that age management should not be implemented as a short-term response to immediate challenges (such as labour shortages), but rather as an integral component of long-term organizational strategy. The importance of the psychosocial work environment is further highlighted by (Gignac et al., 2022), who show that job insecurity and lack of trust reduce older workers' willingness to communicate their needs. A supportive organizational culture therefore represents a key prerequisite for the effective sustainability of employment. (Trentini, 2024) additionally points to the risk of older workers becoming "trapped" in unemployment, emphasizing the need for preventive measures at the organizational level. (Feng et al., 2025) further argue that labour market participation in later career stages has not only economic but also important social and identity-related dimensions. From a synthetic perspective, workforce sustainability can be understood as the result of a complex interaction between competency development, organizational climate, employer perceptions, and broader technological changes. Education, inclusive HR practices, and supportive working environments emerge as key mechanisms through which long-term labour market participation of older workers can be enhanced, while simultaneously mitigating the risk of early exit from the labour market.

GOAL AND METHODOLOGY

The main objective of this study is to provide a comprehensive overview of the research on age management in the context of workforce sustainability. Specifically, the study aims to analyse

the evolution of scientific publications, identify dominant research themes and conceptual approaches, and highlight existing research gaps within the literature. To address these objectives, the following research questions were formulated.

RQ1: How has the volume of scientific publications addressing age management in the context of workforce sustainability evolved over time?

RQ2: What are the dominant research themes and conceptual perspectives in the existing literature on age management and workforce sustainability?

RQ3: What research gaps can be identified in the current body of literature, and what potential directions for future research emerge in the field of age management and sustainable workforce development?

The systematic literature review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a transparent, structured, and reproducible study selection process. In the identification phase, a comprehensive search was carried out using the Web of Science database, which is widely recognized for its high-quality and curated academic content. The search strategy was developed using a combination of relevant keywords and Boolean operators to capture studies addressing age management in the context of labour market outcomes. The search query was formulated as follows:

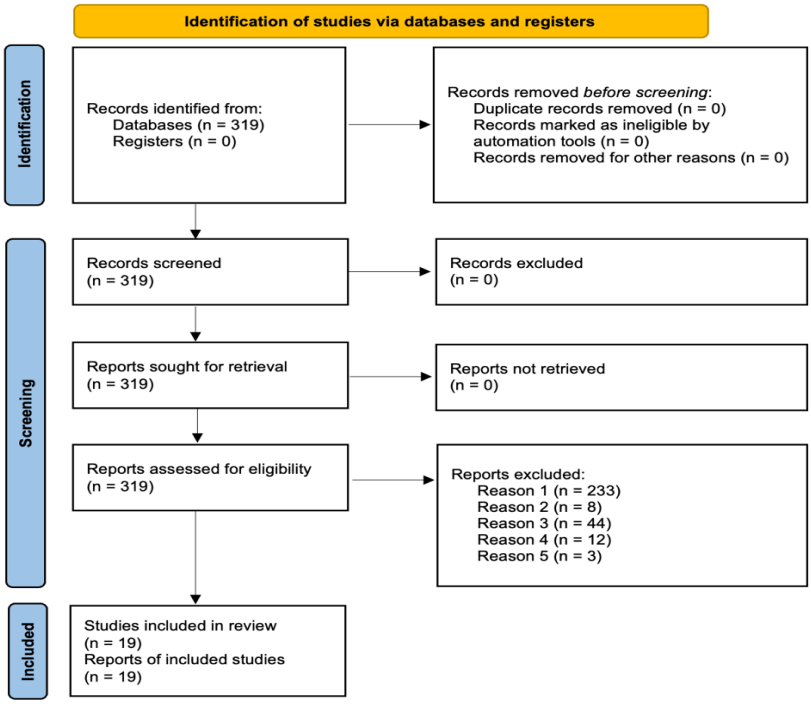
TS = (("age management" OR "aging workforce" OR "older workers") AND (sustainab* OR retention OR employab* OR "working life extension") AND (employment OR "labour market" OR "labor market")).

This initial search yielded a total of 319 records. No additional records were identified through other sources, and no duplicate records were found or removed at this stage.

In the screening phase, all identified records (n = 319) were systematically screened based on their titles and abstracts to assess their preliminary relevance to the research topic. Following this, full-text versions of all records were retrieved and examined (n = 319). No studies were excluded at this stage due to accessibility issues, ensuring that the subsequent eligibility assessment was based on a complete dataset.

In the eligibility phase, a rigorous and sequential filtering process was applied using predefined inclusion criteria. First, a temporal filter was introduced, limiting the sample to studies published between 2021 and 2026 to ensure the timeliness and contemporary relevance of the findings in a rapidly evolving labour market environment (n = 233 excluded, Reason 1). Second, only peer-reviewed journal articles were retained, while other document types such as conference proceedings, book chapters, and editorial materials were excluded to ensure methodological robustness and scientific quality (n = 8 excluded, Reason 2). Third, the selection was restricted to studies classified within the Web of Science categories Management, Sociology, Business, and Demography, thereby ensuring conceptual alignment with the interdisciplinary nature of the research topic (n = 44 excluded, Reason 3). Fourth, only studies indexed in the Social Sciences Citation Index (SSCI) were included to further enhance the academic credibility, impact, and reliability of the dataset (n = 12 excluded, Reason 4). Finally, an additional quality filter was applied by retaining only articles published in journals ranked in the first and second quartiles (Q1 and Q2), thereby ensuring a high level of academic quality and impact (n = 3 excluded, Reason 5).

Figure 1: Systematic study selection process following PRISMA



Source: Own processing based on the PRISMA flow diagram.

Analyses and methods used

This study is methodologically grounded in a systematic literature review conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The application of this approach ensured a transparent, structured, and replicable process of identifying, screening, and selecting relevant scientific publications. As a result of this procedure, a final sample of 19 peer-reviewed journal articles was obtained, focusing on age management and workforce sustainability.

Subsequently, the selected publications were analysed using bibliometric methods implemented in the RStudio environment, specifically through the Bibliometrix/Biblioshiny tool. This analytical approach enabled the examination of key characteristics of the selected literature, including the evolution of scientific production over time, the identification of dominant research themes based on keyword analysis, and the mapping of conceptual structures within the field.

The bibliometric analysis served as a supportive methodological tool, allowing for the identification of prevailing research trends, thematic clusters, and the overall structure of the research domain. In addition, the results provided a basis for detecting underexplored areas and formulating potential directions for future research. To complement the quantitative insights, a qualitative content-oriented interpretation of the selected studies was also conducted, particularly in relation to identifying research gaps and conceptual perspectives within the literature.

FINDINGS

This section presents the results of the bibliometric analysis conducted on a final sample of 19 scientific articles retrieved from the Web of Science database. The analysis focuses on the development of publication activity, dominant research themes, and the conceptual structure of the research field.

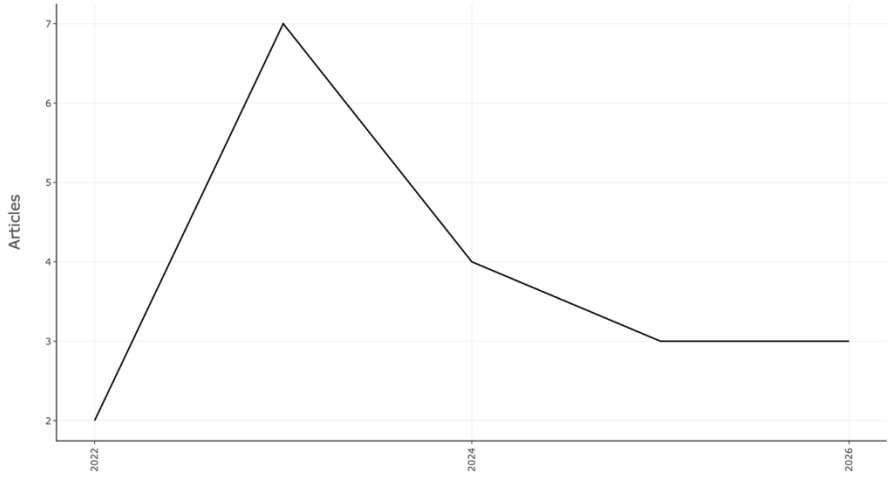
Development of publication activity

The analysis of annual scientific production, based exclusively on data obtained from the Web of Science database, reveals a fluctuating trend in the number of publications addressing age management and workforce sustainability over the observed period (2022–2026). It should be noted that the data for 2026 reflect only the initial phase of the year.

The number of publications increased significantly from 2 articles in 2022 to a peak of 7 articles in 2023, indicating a rapid rise in academic interest in the topic. However, this growth was followed by a gradual decline, with the number of publications decreasing to 4 in 2024 and further to 3 articles in both 2025 and 2026.

As a result of this structured selection procedure, a total of 19 studies met all inclusion criteria and were included in the final review. The number of reports corresponds directly to the number of included studies (n = 19), forming the basis for the subsequent analysis and synthesis.

Figure 2: Annual scientific production, 2022–2026



Source: Own processing in RStudio.

Despite this decline, the publication activity remained relatively stable in the later years, suggesting a sustained, although less dynamic, level of research interest. Overall, the results indicate that while the topic experienced a notable surge in attention in the early phase, it has since transitioned into a more stabilized research area.

Dominant keywords in the literature

The analysis of authors' keywords provides important insights into the dominant research themes within the field of age management and workforce sustainability. The most frequently occurring terms, such as "older workers," "retirement," "age," "employment," and "productivity," indicate that the literature is primarily focused on labour market participation and the economic implications of workforce ageing.

Figure 3: Keyword cloud

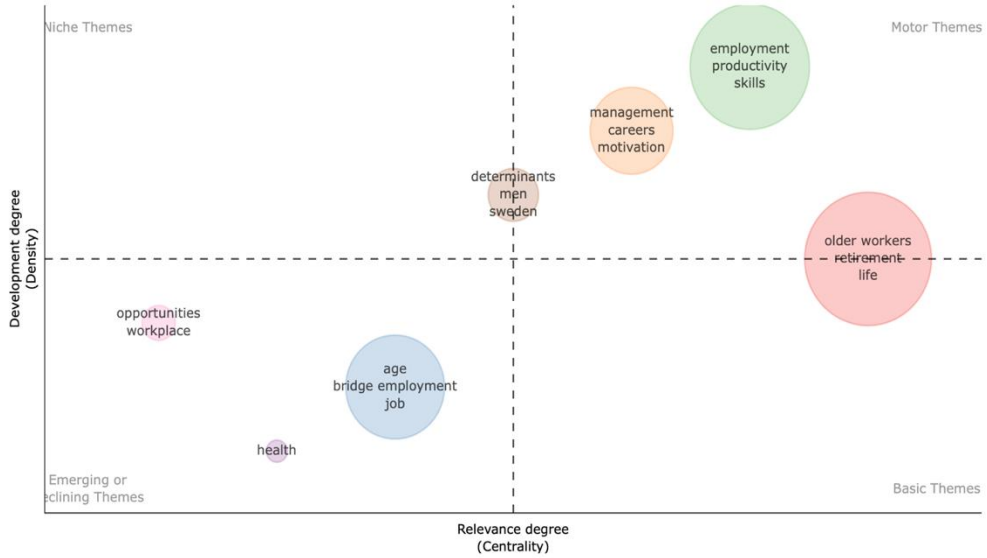
Source: Own processing in RStudio.

A substantial body of research concentrates on late-career employment trajectories, particularly in relation to retirement processes and bridge employment. This suggests that extending working life beyond traditional retirement age represents a central concern in the current literature. In parallel, a significant stream of studies addresses organizational and managerial dimensions, including job management, workplace conditions, and skills development, emphasizing the role of employers in facilitating the integration and retention of older workers.

In addition, the findings highlight the importance of individual-level determinants, such as health status, perceived employability, and attitudes toward ageing, which shape both the capacity and motivation of older individuals to remain economically active. The presence of keywords related to discrimination and ageism further points to persistent structural and social barriers within labour markets. Overall, the keyword analysis suggests that the literature adopts a multidimensional perspective, integrating economic, organizational, and socio-demographic viewpoints in the examination of age management and sustainable workforce development.

The thematic map provides a structured overview of the conceptual landscape of research on age management and workforce sustainability, distinguishing between themes based on their relevance and level of development.

Figure 4: Thematic map



Source: Own processing in RStudio.

The results indicate that the core of the research field is formed by motor themes such as employment, productivity, and skills, as well as management, careers, and motivation. These themes are both highly relevant and well-developed, suggesting that they represent the central focus of the existing literature.

In contrast, themes related to older workers, retirement, and life are positioned among the basic themes, indicating their high importance for the field, but relatively lower level of conceptual development. This suggests that, although widely studied, these topics still offer potential for further theoretical and empirical advancement.

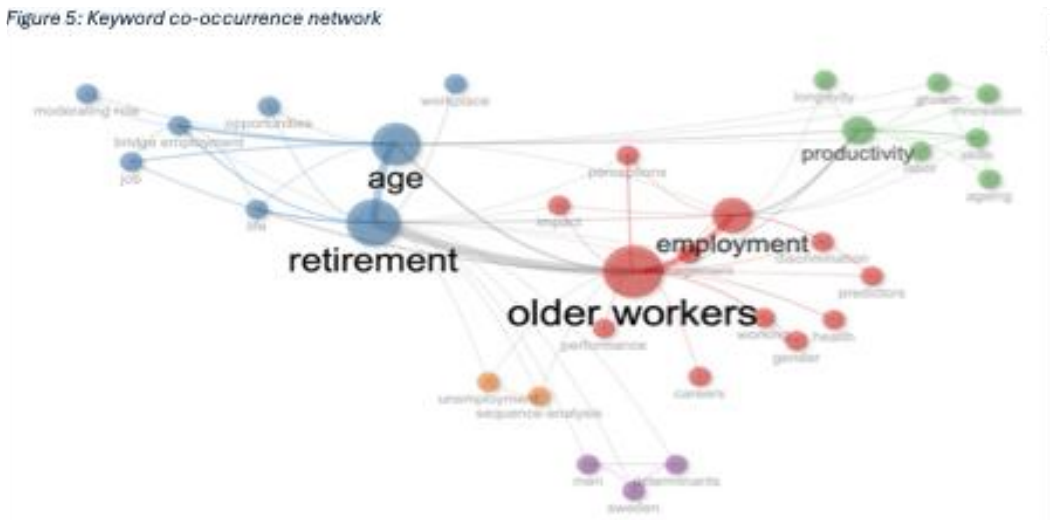
The analysis further reveals a set of emerging or underdeveloped themes, including health, workplace opportunities, and bridge employment. These themes appear to be either newly developing or insufficiently explored within the current literature. Their position in the thematic map highlights their potential significance for future research.

Overall, the findings suggest that while the field is strongly grounded in employment-related and managerial perspectives, there is considerable scope for expanding research toward more diverse and integrative themes, particularly those related to well-being, workplace conditions, and non-linear career trajectories in later life.

Network of key themes and research streams

The structure of the research field can be better understood through the co-occurrence network of authors' keywords, which highlights the relationships between the most frequently used concepts. Several interconnected thematic clusters emerge, with older workers, retirement, age, and employment forming the central backbone of the network.

Figure 5: Keyword co-occurrence network



Source 5: Own processing in RStudio.

Among these, older workers and retirement stand out as dominant focal points, reflecting the strong orientation of the literature toward labour market participation in later life. The dense interconnections between these terms indicate a high level of internal consistency and thematic integration across studies. A closely related group of keywords revolves around employment-related dimensions, including management, performance, and health. This cluster emphasizes the role of both organizational practices and individual characteristics in shaping employment outcomes for older workers. The inclusion of terms such as gender and discrimination further underlines the importance of social and structural influences within this domain. In parallel, another cluster centred on productivity, skills, and innovation points to an increasing research focus on the economic value and capabilities of ageing employees. This shift suggests that the literature is gradually moving beyond participation toward a deeper understanding of performance and contribution in later working life. Attention is also given to transitional employment patterns, as reflected in the cluster containing bridge employment, job, and opportunities. These terms indicate interest in flexible and non-linear career pathways. At the same time, smaller and more loosely connected clusters, including those linked to specific national contexts or demographic subgroups, suggest the presence of more specialized lines of inquiry. Taken together, the network illustrates a well-developed and interconnected research area, primarily centred on employment and retirement dynamics, while also pointing to emerging directions related to skills development, innovation, and alternative career trajectories. To provide a more detailed overview of the analysed studies, a structured summary was developed focusing on their research objectives, theoretical foundations, and methodological approaches. This allows for a deeper understanding of how age management and workforce sustainability have been conceptualized and examined in the existing literature.

Table 1: The main characteristics of the analysed studies

Authors	Goal	Theory	Methodology and data analysis
Lugova et al. (2026)	Examines the impact of delayed retirement on mental health and job quality among older workers	Life course perspective; Job quality framework	Quantitative study; cross-national data; regression analysis
André et al. (2026)	Analyses labour market participation of older workers with a focus on policy implications	Labour market theory; Active ageing framework	Comparative macro-level analysis; secondary data
Lee et al. (2026)	Investigates employer perceptions of older workers and their influence on hiring decisions	Ageism theory; Employer perception framework	Quantitative study; survey data; regression analysis
van der Heijden & Vermeeren (2025)	Explores sustainable employability and willingness to continue working in later life	Sustainable employability theory; Career sustainability perspective	Quantitative study; survey data; structural equation modelling (SEM)
Chen et al. (2025)	Examines the role of intergenerational interactions in shaping employability of older workers	Social exchange theory; Intergenerational learning	Quantitative study; survey data; structural equation modelling (SEM)
Li et al. (2023)	Investigates the impact of lifelong learning on intention to remain employed after retirement age	Human capital theory; Lifelong learning framework	Quantitative study; survey data; regression analysis
Naegele et al. (2022)	Analyses access to training and age-related differences in participation in learning activities	Human capital theory; Age diversity perspective	Conceptual and qualitative analysis
Lagacé et al. (2022)	Examines knowledge sharing practices and their impact on engagement of older workers	Knowledge management theory; Social exchange theory	Quantitative study; survey data; structural equation modelling (SEM)
Marcaletti et al. (2023)	Explores the relationship between training participation and job quality among older workers	Employability theory; Job quality framework	Quantitative study; regression analysis

Low et al. (2024)	Investigates the role of digital and AI-related skills in career resilience of older workers	Human capital theory; Career resilience framework	Quantitative study; structural equation modelling (SEM)
Xie et al. (2023)	Examines how digital training affects autonomy and employability of older workers	Self-determination theory; Digital competence framework	Quantitative study; survey data; structural equation modelling (SEM)
Meng et al. (2022)	Analyses the impact of age discrimination and managerial attitudes on job loss risk	Age discrimination theory; Labour market theory	Longitudinal quantitative study; regression analysis
Binyamin & Brender-Ilan (2022)	Examines communication climate and its impact on attitudes toward middle-aged workers	Organizational communication theory	Quantitative study; survey data; structural equation modelling (SEM)
Jensen et al. (2023)	Investigates the relationship between age stereotypes and HR practices	Ageism theory; HRM perspective	Quantitative study; survey data; regression analysis
Neupane et al. (2022)	Defines and analyses sustainable employability as a multidimensional construct	Sustainable employability theory	Conceptual study
Verdonk et al. (2023)	Critically examines existing definitions of sustainable employability	Critical perspective; Sustainability framework	Conceptual analysis
Mazumdar et al. (2023)	Explores bridge employment and its effects on attitudes of older workers	Life course theory; Career transition theory	Quantitative study; survey data; regression analysis
Hallpike et al. (2024)	Investigates strategies for optimizing career sustainability in later life	Career sustainability theory	Qualitative study; interviews
Sousa-Ribeiro et al. (2023)	Examines post-retirement employment and factors influencing continued work	Active ageing theory; Work engagement theory	Quantitative study; survey data; structural equation modelling (SEM)

Table 1 summarizes the main characteristics of the analysed studies, including their research focus, theoretical background, and methodological approaches. The results indicate a strong dominance of quantitative research designs, particularly survey-based studies employing regression analysis and structural equation modelling techniques.

In relation to RQ3, the analysis indicates that the current literature contains several important research gaps. Although age management is frequently linked to employability, retirement and the extension of working life, the concept of workforce sustainability is often addressed only indirectly. This suggests the need for future studies to examine age management more explicitly as a strategic tool for supporting long-term organizational sustainability. Another underdeveloped area concerns the impact of digital transformation, automation and artificial intelligence on older workers. Future research should therefore focus more systematically on how digital competencies, technological change and lifelong learning influence the employability, productivity and inclusion of older employees. The findings also point to a lack of empirical evidence on the effectiveness of specific age management practices, such as flexible work arrangements, intergenerational knowledge transfer, health promotion and inclusive HR policies. Further research should adopt a more integrative and comparative approach, combining individual, organizational and policy-level perspectives. Such an approach would allow for a deeper understanding of how age management practices differ across institutional and cultural contexts and how they contribute to sustainable workforce development.

DISCUSSION

This study aimed to systematically map the current state of research on age management in the context of workforce sustainability and to identify key research trends, conceptual perspectives, and gaps that can inform future research. The findings provide a comprehensive overview of how this research field has developed and how it is currently structured.

The analysis of publication activity (RQ1) indicates that research on age management and workforce sustainability has gained attention relatively recently, particularly after 2022. The sharp increase in publications observed in 2023 suggests a growing recognition of demographic ageing as a critical issue for labour markets and organizations. Although a slight decline in publication output was observed in subsequent years, the overall trend points to a stabilization of research activity, indicating that the topic is gradually becoming an established area of scholarly inquiry. This development reflects broader socio-economic challenges, including population ageing, labour shortages, and the need to extend working lives. The thematic and keyword analyses (RQ2) reveal that the literature is strongly centred on labour market participation of older workers, retirement processes, and employment-related outcomes. Core themes such as older workers, retirement, employment, and productivity dominate the research field, highlighting the economic dimension of workforce ageing. At the same time, the presence of themes related to skills, health, and management indicates that the literature incorporates organizational and individual perspectives. The co-occurrence network and thematic map further demonstrate that the field is characterized by a relatively high degree of conceptual cohesion, with strong interconnections between key themes. Motor themes such as employment, productivity, and skills represent the core of the research area, suggesting that these topics are both well-developed and central to the existing literature. In contrast, themes such as health, workplace opportunities, and bridge employment are positioned as emerging or underdeveloped, indicating areas where further research is needed. The results also highlight the multidimensional nature of the research field, combining economic, organizational, and socio-demographic perspectives. However, despite this diversity, the literature remains somewhat fragmented, with limited integration across different levels of analysis. There is a noticeable imbalance between macro-level studies focusing on labour market structures and policies and micro-level research examining individual experiences and workplace dynamics.

In relation to research gaps (RQ3), several important limitations of the current literature can be identified. First, the concept of sustainability is often addressed implicitly rather than explicitly. While many studies focus on extending working life or improving employability, fewer studies examine age management as a strategic component of long-term organizational sustainability. This suggests a need for future research to more clearly integrate sustainability frameworks into age management research. Second, the role of digital transformation and technological change remains insufficiently explored. Given the increasing importance of digital skills, automation, and artificial intelligence, future research should

examine how these factors influence the employability, productivity, and inclusion of older workers. This represents a particularly relevant area for further investigation in the context of rapidly evolving labour markets. Third, although the literature acknowledges the importance of health, well-being, and working conditions, these aspects are often treated as secondary factors rather than central research themes. Future studies should therefore place greater emphasis on the relationship between extended working life and individual well-being, including potential trade-offs between productivity and quality of life. Another important gap concerns the limited focus on specific organizational practices and interventions. While age management is frequently discussed at a conceptual level, there is less empirical evidence on the effectiveness of concrete HR practices and managerial strategies. Future research could provide more detailed insights into how organizations can successfully implement age management policies in practice.

Furthermore, the literature shows limited geographical diversity and a lack of comparative studies. Cross-national differences in labour market institutions, cultural norms, and policy frameworks suggest that age management practices may vary significantly across contexts. Future research should therefore adopt a more comparative perspective to better capture these differences. From a theoretical perspective, the findings indicate that the literature draws on a range of theoretical frameworks, including human capital theory, sustainable employability, life course theory, and social exchange theory. However, these frameworks are often applied in isolation, with limited efforts to develop integrative theoretical models. Future research could benefit from combining these perspectives to develop a more comprehensive understanding of age management and workforce sustainability. In addition to theoretical implications, the findings also have important practical relevance. The results suggest that organizations should adopt a more strategic and proactive approach to age management, focusing not only on extending working life but also on enhancing the quality of work, supporting continuous learning, and fostering inclusive workplace environments. Leadership, organizational culture, and HR practices play a critical role in shaping the experiences and outcomes of older workers. However, like any study, this research has several limitations. First, the analysis is based exclusively on the Web of Science database, which may limit the coverage of relevant studies, particularly those published in other databases or in non-indexed journals. Second, the study focuses on a relatively small sample of 19 articles, which reflects the strict inclusion criteria but may limit the generalizability of the findings. Third, the interpretation of thematic structures and research trends is partly subjective, as it depends on the analytical choices made during the bibliometric and content analysis. Despite these limitations, the study provides a valuable contribution by offering a structured overview of the research field and identifying key areas for future investigation. The combination of bibliometric analysis and qualitative interpretation ensures a comprehensive and robust approach to understanding age management in the context of workforce sustainability.

CONCLUSION

This study provides a comprehensive overview of the current state of research on age management in the context of workforce sustainability. The findings show that academic interest in this field has increased in recent years, reflecting the growing importance of demographic ageing, labour shortages and the need to extend working lives. As organizations are increasingly required to maintain the employability, productivity and well-being of an ageing workforce, age management is becoming an important area of both academic research and managerial practice. The analysis identified several dominant research trends, particularly those centred on employment, retirement, productivity and the labour market participation of older workers. At the same time, the findings point to the growing relevance of themes such as skills development, lifelong learning, health, well-being, digital competencies and non-linear career paths. These themes indicate that age management should not be understood only as a response to population ageing, but also as a broader strategic approach aimed at supporting employees throughout different stages of their working lives.

The study also reveals several important research gaps. Existing literature still pays limited attention to the explicit integration of sustainability perspectives into age management research. Although many

studies focus on employability and the extension of working life, fewer studies examine how age management contributes to long-term organizational sustainability. In addition, digital transformation, automation and artificial intelligence remain underexplored in relation to older workers. Future research should therefore examine how technological change affects the skills, adaptability, inclusion and career resilience of ageing employees. Another important gap concerns the limited empirical evidence on the effectiveness of concrete organizational age management practices. Further studies should investigate how specific HR practices, such as flexible work arrangements, lifelong learning, intergenerational knowledge transfer, health promotion and inclusive leadership, contribute to sustainable workforce development. Future research would also benefit from more comparative and multi-level approaches that combine individual, organizational and policy-level perspectives. Such approaches could provide a deeper understanding of how age management practices differ across institutional, cultural and labour market contexts. However, the study has several limitations, particularly those related to the design of the systematic literature review. First, the analysis is based exclusively on the Web of Science database, which may have led to the exclusion of relevant studies indexed in other academic databases. Second, the search strategy relied on a specific combination of keywords and Boolean operators; therefore, studies using alternative terminology related to age management, older workers or workforce sustainability may not have been captured. Third, the inclusion criteria restricted the sample to peer-reviewed journal articles published between 2022 and 2026 and classified within selected Web of Science categories. While these criteria enhanced the relevance, quality and consistency of the analysed literature, they may also have limited the breadth of the review by excluding older studies, conference papers, book chapters and grey literature. In addition, the final sample consisted of a relatively small number of selected studies, which may limit the generalizability of the findings. Finally, although bibliometric analysis provides a structured overview of the research field, the interpretation of thematic structures, clusters and research gaps involves a certain degree of subjectivity and is influenced by the selected keywords, inclusion criteria and analytical procedures. Despite these limitations, the study contributes to the existing literature by providing a structured overview of current research trends, identifying underdeveloped areas and outlining key directions for future research in the field of age management and sustainable workforce development.

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REQUIRED TECHNICAL COMPETENCIES NECESSARY FOR PROFESSIONAL PRACTICE IN INDUSTRIAL ENGINEERING AND MANAGEMENT

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Abstract

This article addresses the evolving demands placed on industrial engineers and managers within the context of rapid organizational and technological advancements, specifically influenced by factors arising from the social, legislative, economic, and technological environments. The core of the study lies in identifying the essential technical and practical competencies required for successful application in modern industrial engineering and industrial enterprise management. Technological progress, marked by widespread digitalization, is fundamentally altering the character of engineering work, shifting focus towards advanced data analysis, simulation, software proficiency, and predictive control.

Key words: *business management, digitalization, engineer competencies, industrial engineering, process optimization*

JEL Classification M1, M12, O3, C44 https://doi.org/10.52665/ser20260105

INTRODUCTION

Industrial engineering is a field that is constantly evolving. The requirements for industrial engineers are shaped by organizational development, which is influenced by various external factors resulting from the development of the social, legislative, economic and technological environment. Technological progress is not only changing the work of workers in industry, but also the character of the work of an engineers. Digitalization allows for various analyses and simulations, but also increases the need to control and perform these analyses, with the need for predictive management coming to the fore. In particular, industrial engineers should be able to ensure the production and standard course of processes and procedures taking place in production. The main task of process engineers is to optimize processes in production, whether in terms of their efficiency, quality or cost. For this important role, it is necessary for industrial engineers and managers to have the necessary skills that take into account all aspects of an industrial engineer's job.

THEORETICAL BACKGROUND

Managers of industrial enterprises face many challenges regarding the effective management of industrial enterprises. Addressing inefficiencies is particularly crucial in the early stages of processes, as it can lead to substantial cost reductions, which is already evident in the current industrial environment (Dulina et al., 2025). Effective resource management is a critical challenge. Efficient resource allocation is intended to reduce costs and increase profits. Successfully overcoming these challenges requires the use of advanced intelligent information systems that optimize costs, production time, and profits (Al-yasin et al., 2025). The implementation of advanced systems enables real-time control and monitoring of industrial processes. New technologies make it possible to move the industrial agenda far beyond the capabilities of conventional systems through digitization. Advanced real-time data analytics make it possible to improve efficiency and productivity in industries in particular (Nechibvute & Mafukidze, 2024). The technological side in the management of industrial enterprises is often emphasized in connection with the introduction of smart industry (Moraes et al., 2023). Traditional production processes are gradually being replaced by smart technologies. Smart manufacturing systems make it possible to leverage IT and collect large amounts

of data in real time, which are then analyzed to make accurate decisions and predict future outcomes in order to improve the efficiency of manufacturing operations. However, coordination between machines and humans is essential for effective functioning. This is made possible by large-scale data analysis, which makes the methods of analysis and productivity of production units simple and fast (Gupta et al., 2022). Organizations must adapt to rapidly evolving technologies, which requires the need for systems engineering, robust information management, and collaboration. However, key engineering skills must also mature to achieve the desired result (Kempton & Waldon, 2024). The integration of new technologies, or the combination of technologies, can bring major benefits to the industry in increasing data transparency and efficiency. However, there are still some challenges that need to be addressed, such as the interoperability of individual data protection and security systems, and the need for qualified personnel (Dwivedi et al., 2024). The introduction of intelligent industry elements into organizations has an impact not only on the operation of industrial enterprises, but also on the people who work in them. The need for qualified workers is growing and employers' demands for a higher level of education are also growing. Technological changes require in particular vocational training and the development of technical skills. Increasing the professionalism of employees can enable them to cope with new technologies in the best possible way (Grenčíková et al., 2021). Industrial engineers have a major impact on the functioning of enterprises and the introduction of smart industry. Their competencies have a positive impact on the implementation and management of smart industry technologies. The most important competencies related to production security and prediction of the development of production scenarios, reflecting technological progress and introducing technologies were demonstrated. In the context of intelligent industry, the importance of competencies related to automation and robotization, or cloud solutions, is growing in importance (da Rocha et al., 2025). Among education experts and specialists in the field of intelligent industry and Industry 4.0, discussions are still ongoing about the new challenges of Industry 4.0 for industrial engineers. Despite these discussions, there is no consensus on which competencies are required of industrial engineers to face these new challenges (Rosas Quintero & Namuche Maldonado, 2024). Technical skills remain at the core of engineering despite the fact that the working conditions and tasks of engineers have changed and the so-called hard engineering is shifting to the so-called soft engineering (Nguyen, 1998). In engineering, emphasis is placed on practical engineering as an integrated competence that appears to be the most important integrated design capability (Suleiman & Abahre, 2020). In order for technological progress and its potential to be fully exploited, it is not enough to have integrated high-quality technologies, but it is also necessary to have people who will enable the use of these technologies and their proper functioning (Hitka et al., 2023). The ability to work with modern technologies, but also the ability to use digital tools for process control to analyze data and is becoming an essential skill for future professionals (Bolek, 2025). Therefore, it is important that engineers and industrial managers in industrial enterprises in particular have competencies that are important for the correct deployment of technologies and the functioning of processes in the organization.

OBJECTIVE AND METHODOLOGY

Given the importance of technical competencies for the work of a manager, we decided to examine which technical competencies are considered important by employers. Technical competencies were divided into two groups, namely I. Technical operational competencies and II. Technical conceptual competencies. For the purposes of the study, we set three research questions:

RQ1: What are the current technical competencies requirements for industrial engineers and managers?
RQ2: To what extent are technical competencies of industrial engineers and managers required in industrial enterprises in Slovakia?
RQ3: How do the technical competencies requirements for industrial engineers and managers differ?
The aim of the presented study was to analyze the current priorities in the requirements for the technical competencies of industrial engineers and managers of industrial enterprises. For the study, we chose a qualitative design and a descriptive approach. Advertised job descriptions and job vacancy requirements specifications in the field of industrial engineering and management were analyzed for the purpose of the

study. The advertisements were obtained from advertising portals in Slovakia. The collection of advertisements took place in the period February 2025 – April 2025. The selection criterion was that the advertisements contained requirements for positions that were denoted as "Industrial Engineer" or "Process Engineer" or "Industrial Manager". For the purpose of the study, 40 advertisements were searched. Each advertisement was transcribed into a structured database in MS Excel. Relevant sections on the job description, powers and responsibilities and requirements for the applicant were extracted from the texts of the advertisements. Subsequently, a qualitative analysis of the content was carried out in the form of a thematic analysis. Based on reading and analyzing the texts of the advertisements, coding was done. Competency categories have been created for similar codes. Based on the results of profiling the competencies of industrial engineers and managers, we determined their importance according to which competencies were repeated most often. To interpret the results, we chose descriptive statistics in the form of tables. In Table 1, we can see a description of the structure of the examined sample of 40 job advertisements.

Table 1: Number of jobs hired

Job Title	Absolute abundance	Relative abundance [%]
Industrial Manager	8	20.00
Process Engineer	17	42.50
Industrial Engineer	15	37.50
Total	**40**	**100.00**

Source: own processing, 2025

Table 1 shows that a total of 40 advertised jobs were analysed. The highest number was 17 jobs – Process Engineer (42.5%) and the smallest number was for the job position – Industrial Manager (20%).

RESULTS AND DISCUSSION

Empirical research aimed at identifying key technical competencies was carried out through a detailed content analysis of advertised job positions on leading Slovak professional portals. As previously stated, the analytical efforts focused on three key professional profiles: industrial engineer, process engineer and industrial manager. The initial step of the analysis was to map the regional distribution of the data obtained, as the demand for specific engineering competencies is closely related to the concentration of industrial production in individual parts of Slovakia. The geographical structure of the examined sample of 40 job advertisements, divided by individual self-governing regions, is clearly illustrated in Table 2.

Table 2: Distribution of analysed job advertisements by region

Region	Absolute abundance	Relative frequency [%]
Banská Bystrica	12	30.00
Bratislava	4	10.00
Košice	2	05.00
Nitra	3	07.50
Prešov	1	02.50
Trenčín	10	25.00
Trnava	5	12.50
Žilina	3	07.50
Total	**40**	**100.00**

Source: own processing, 2025

The data presented in Table 2 show that the most significant representation in the demand for industrial engineers and managers is shown by the Banská Bystrica Region with a share of 30.00% (12 advertisements), closely followed by the Trenčín Region, where 25.00% (10 advertisements) of the total volume of job vacancies were identified. A significant part of the labour market in this area is also represented by the Trnava Region (12.50%) and the Bratislava Region (10.00%). On the contrary, the lowest offer of vacancies meeting the selection criteria was recorded in the Košice Region (5.00%) and the Prešov Region, which makes up only 2.50% of the research sample with one advertisement. These results reflect the regional concentration of industrial companies and automotive clusters, which naturally show a higher demand for experts in the field of industrial engineers.

Evaluation of RQ1: *What are the current technical competencies requirements for industrial engineers and managers?*

As part of the processing of the results related to the first research question, an in-depth thematic analysis of the texts of the advertised job positions was carried out. Based on the coding of employers' requirements, it was found that the demands on the technical readiness of applicants are naturally concentrated in mutually complementary areas. As a key theoretical and practical result of this phase of research, the division of technical competencies into two main thematic groups was defined: (1) Technical operational competencies and (2) Technical conceptual competencies. When evaluating the research question, we first focused on Technical operational competencies, which are necessary to ensure the proper functioning of production operations.

Table 3: Overview of identified Technical operational competencies

Code	Category / Area of competence	Detailed description of the requirements from the advertisements
A	Device management and setup	Planning and ensuring the correct operation of technological and additional equipment, setting the parameters of machines and equipment.
B	Product launch	Introduction and classification of new products into serial production, component quality planning (CQA process) and pricing.
C	Technological support and testing	Control of technological processes and technical support, selection and implementation of appropriate technological procedures and performance of technological tests.
D	Process development and optimization	Planning, development and classification of new production processes, definition and optimization of process parameters.
E	Renewal of machinery	Participation in the selection of new machines and equipment, installation of new equipment and their introduction into operation.
F	Design solutions	Design and implementation of new structural solutions of jigs.
G	Metrology and quality	Security, definition and analysis of measuring instruments and measurement systems.

Source: own processing, 2025

From the data in Table 3, it is clear that technical operational competencies were divided into seven separate categories marked with codes A to G based on thematic analysis. The assigned coding creates a systematic basis for an exact evaluation of the frequency of occurrence of individual requests in the next phases of the analysis. From the point of view of the job description, the dominant feature of these competencies is their direct connection to ensuring the stability, quality and fluency of the physical course of the production process.

Following on from the previous breakdown, Table 4 presents six categories of Technical conceptual competencies, which have been coded H to M. Technical conceptual competencies are important primarily in the design of workplaces and for the implementation and improvement of processes.

Table 4: Overview of identified Technical conceptual competencies

Code	Category / Area of competence	Detailed description of requirements from advertisements
H	Design and ergonomics	Workplace design, layout changes based on the principles of ergonomics and occupational health and safety, creation of material flows.
I	Performance Management (KPIs)	Support for defining, implementing, and tracking KPI metrics for processes with a focus on quality, productivity, and cost.
J	Strategic maintenance planning	Participation in the design of the strategy and the creation of plans in the field of maintenance, modernization and renewal of machines.
K	Tool and inventory management	Creating a list of tools, monitoring their stock levels and collaborating on ordering new ones.
L	Change Management	Planning and implementing changes in production.
M	Process monitoring and stability	Monitoring, analysis and evaluation of configured production and non-production processes, analysis of process stability, control of compliance with parameters.

Source: own processing, 2025

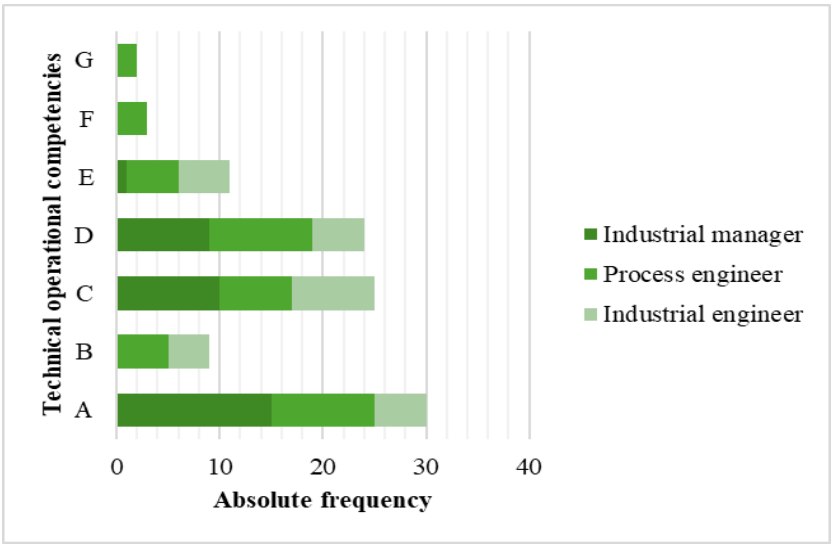
The competencies listed in Table 4 reflect the shift from purely operational activities to a systemic understanding of an industrial enterprise, dominated by the spatial arrangement of flows (code H) and strategic planning of innovation (code J). An important component of this group is the emphasis on data-driven management through the introduction of KPI metrics (code I) and continuous evaluation of process stability (code M). Together, these components define the analytical profile of an industrial engineer or manager who is able not only to keep production systems running, but also to systematically develop them and manage their changes.

Evaluation of RQ2: *To what extent are technical competencies of industrial engineers and managers required in industrial enterprises in Slovakia?*

To determine the extent and degree of demand for individual technical skills, the absolute frequency of occurrence of codes in 40 collected advertisements was analyzed. The results of this analysis are broken down into two main groups of competences and visualised in the attached graphs (Figure 1 and Figure 2). A graphical representation of the absolute frequency of occurrence of individual operational competencies in the analysed advertisements is provided in Figure 1. The identified competencies are marked on the vertical axis of the graph with codes A to G, which correspond in meaning and content to the detailed categorization given in the previous Table 3.

Figure 1 graphically illustrates the absolute frequency of demand for Technical operational competencies (codes A to G from Table 3) within the 40 advertisements analysed, visually distinguishing the contribution of the three monitored job positions. From an overall point of view, the competency of equipment management and setup (code A) dominates, with the highest incidence at the level of 30 records, where a significant share is the position of Industrial manager, followed by a balanced demand for technological support (code C) and process development (code D), where the Process engineer is strongly represented. On the contrary, the lowest overall frequency within the entire sample is reported by the areas of design solutions (code F) and metrology (code G), which do not appear in the offers for industrial managers at all and are only minimally represented in process and industrial engineers. The composition of the individual columns thus clearly confirms that while the operational core A, C, D is universally required across all three professions, specific activities such as the introduction of new products (code B) are the domain of process and industrial engineers only.

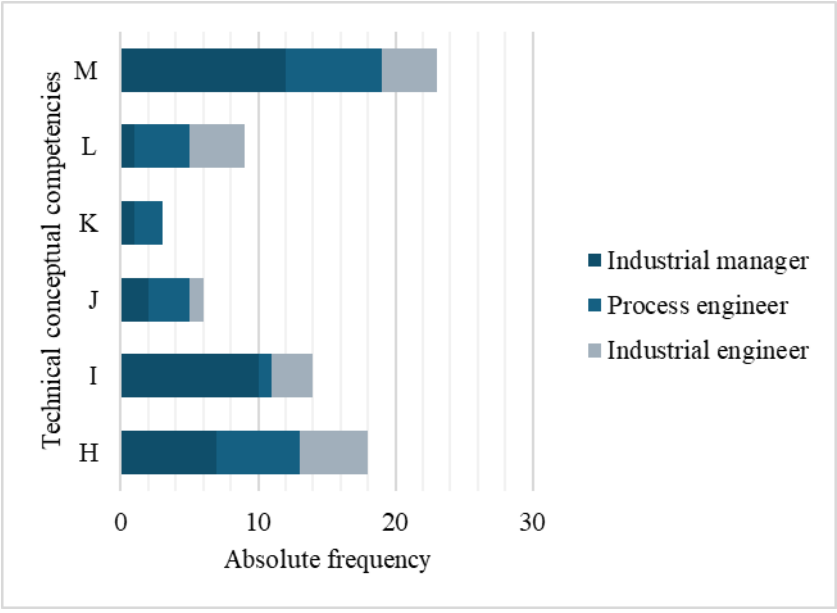
Figure 1: Absolute frequency of requests for Technical operational competencies by job position



Source: own processing, 2025

After the analysis of engineering activities, the attention of the study shifts to the second, strategic-analytical dimension of labor market requirements. For a comprehensive view of the qualification profile, it is necessary to examine the scope of demand for system competencies, which have been defined in the methodological part as Technical conceptual competencies. The distribution of the absolute abundance of these competencies and their distribution among individual job positions is illustrated in Figure 2, while the designations H to M used on the vertical axis of the graph directly refer to the six conceptual categories described in detail in the previous Table 4.

Figure 2: Absolute frequency of requests for Technical conceptual competencies by job position



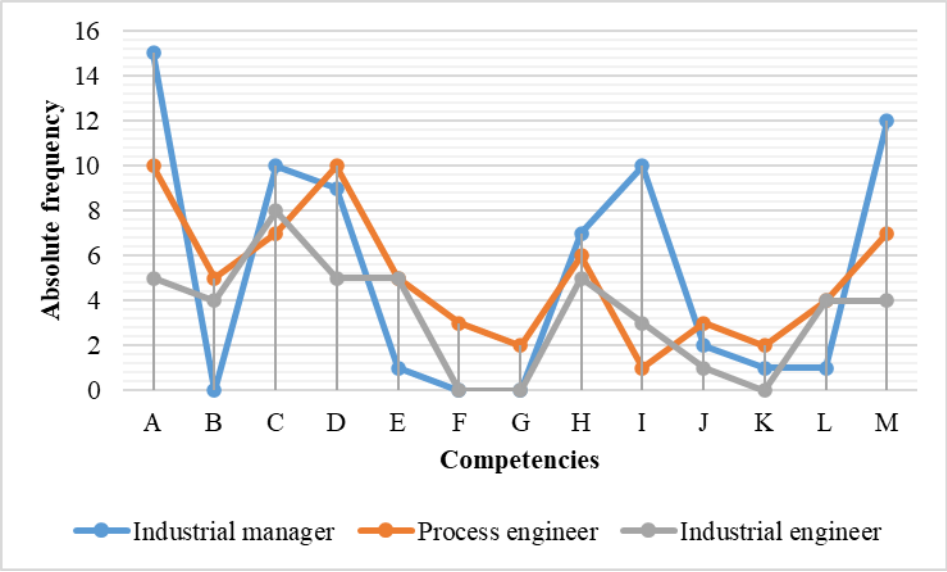
Source: own processing, 2025

Figure 2 demonstrates the absolute abundance of technical conceptual competency requirements (codes H to M from Table 4), revealing a clear dominance of two key areas. The highest frequency of occurrence is achieved by competence M focused on monitoring, analysis and stability of processes with a total of 23 records, closely followed by the H coding, which represents the design of workplaces and material flows with 18 occurrences. From the point of view of the structure of job positions, it is clear that while process analysis (code M) and layout changes (code H) show a balanced demand across all three professions, the area of performance management and KPI metrics (code I) is mostly required for the position of Industrial manager with 14 occurrences. At the opposite end of the spectrum, with minimal interest from employers, was tool and inventory management (code K), which achieved only 3 occurrences, while in advertisements for industrial engineers (Industrial engineer) this requirement is completely absent, as well as strategic maintenance management (code J).

Evaluation of RQ3: *How do the technical competencies requirements for industrial engineers and managers differ?*

To answer the third research question, we used a comparative analysis to identify specific differences and priorities in employers' requirements for the three monitored professional profiles: Industrial manager, Process engineer and Industrial engineer. To accurately capture these differences, the distribution of all thirteen identified competencies was monitored at the same time. A summary view of demand variability and mutual differences in the profiles of individual positions is provided in Figure 3, where designations A to G represent technical operational competencies (from Table 3) and designations H to M represent technical conceptual competencies (from Table 4).

Figure 3: Comparison of the absolute frequency of required competencies by job position



Source: own processing, 2025

The visual comparison in Figure 3 reveals significant differences in the profiles of labour market demands, with the most significant anomalies being shown by the position of Industrial Manager. Three competencies in particular are critical for this managerial role: plant operation and setup (code A, 15 occurrences), process monitoring and stability (code M, 12 occurrences) and performance management through KPI metrics (code I, 10 occurrences), while narrowly focused engineering activities such as new product introduction (code B) or tool management and design (codes F, G, K), They are completely absent

from managers. On the other hand, the process and industrial engineer profiles show a high degree of synergy in the graph and follow a similar course of curves. A more significant differentiation between them occurs in code D (Planning and development of new production processes), where employers place significantly higher emphasis on process engineers (10 occurrences compared to 5 occurrences in industrial engineers), and code C (Control of technological processes), where industrial engineers slightly dominate. The resulting comparative graph thus clearly proves that while engineering positions are primarily focused on technical implementation, process development and solving specific technological tasks, the profile of an industrial manager is strictly shaped by the market towards executive stability management, performance control and achievement of set goals.

However, for all three analysed professions, primary technical competencies are important for these professionals to be applicable and successful in professional practice.

Highly qualified employees are consistently in demand across all industries. Low-skilled and semi-skilled workers are only relevant in specific sectors, such as end-user customer service in the manufacturing sector (e.g. clothing, furniture and consumer electronics). In the manufacturing sector, a massive shift in job requirements (low-skilled and semi-skilled workers) is expected due to technological changes involving the Internet of Things, cloud technologies, and big data analytics. To some extent, polarization in the manufacturing sector can be determined by job competencies and the level of automation (Janis & Alias, 2018). However, a significant shortage of technological skills competencies has been identified in various sectors. A growing lack of competence in terms of quantity but also quality, which has an impact on innovation and the competitiveness of enterprises. Competency shortages are not only a short-term but also a medium-term challenge for businesses (Ebert & Hemel, 2023).

The competency challenges for new technologies are multifaceted and include the integration of advanced technologies as well as addressing educational gaps.

CONCLUSIONS

Cooperation between universities and practice plays an important role in the preparation of future industrial engineers and managers, correcting the requirements for the content focus of the study. However, solid theoretical training requires the application of various forms of education, enabling participation in the solution of specific practical problems and the development of practical skills and lifelong learning. The management of industrial enterprises must also focus on developing qualified personnel and ensuring the safe and efficient introduction of new technologies to maintain competitiveness and promote innovation.

The results of our analysis clearly show that academic training must reflect the dual nature of labour market expectations, which requires graduates not only to master traditional operational activities, but also to an increasing extent to conceptual and analytical thinking. The connection between the academic environment and the industrial sphere should therefore focus more intensively on the development of skills in the field of data analytics, monitoring KPI metrics and designing modern ergonomic workplaces. Graduates with this combination of knowledge are able to respond much more flexibly to the regional needs of companies, which is also confirmed by the high concentration of demand for these experts, especially in the Banská Bystrica and Trenčín regions. Under the influence of digitalization, conventional engineering is thus turning into a complex managerial and technological system, in which the success of an organization directly depends on the readiness and continuous development of its human capital. The results of our analysis confirm that the labor market requires a dual graduate profile, where traditional operational skills must intertwine with conceptual thinking, data analytics and change management. It is this flexibility that is the key to meeting the needs of businesses, especially in the industrially strong Banská Bystrica and Trenčín regions.

The main limitation of the submitted study is the size of the research sample (40 advertisements) and its time limit to a three-month period of 2025, which limits the full generalization of the results. In addition, the analysis is based exclusively on the texts of the advertisement, which may not one hundred percent

reflect real everyday practice. Future research should therefore focus on expanding the sample and integrating a questionnaire survey or guided interviews directly with experts from industrial companies.

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DATA ANONYMIZATION IN WASTE MANAGEMENT: CHALLENGES, METHODS, AND AI-DRIVEN APPROACHES

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Abstract

The digital transformation of waste management systems—encompassing Radio Frequency Identification (RFID)-equipped collection bins, Global Positioning System (GPS)-tracked vehicles, sensor-based smart containers, and pay-as-you-throw (PAYT) billing—generates continuous streams of data that carry significant privacy implications. These data intersect personal, commercial, and operational interests of municipalities, citizens, waste-collection companies, producer responsibility organisations (PROs), regulators, and researchers. Waste management presents sector-specific challenges that remain underexplored: the physical tangibility of waste enables re-identification even after digital anonymization; PAYT systems expose household behavioural patterns; and industrial waste data constitute commercially protected trade secrets. This paper analyses the anonymization requirements of all major stakeholder groups, reviews legal obligations, and proposes a layered anonymization workflow grounded in operational practice at waste-collection operators. Both classical and emerging AI-driven techniques are evaluated—including differential privacy, NLP/NER-based document redaction, OCR pipelines, computer-vision anonymization, Vision-Language Models (VLMs), agentic LLM pipelines, synthetic data generation, and federated learning. A strict requirement for all AI-driven methods is on-premise deployment. A comparative analysis against water, energy, and telecommunications utilities highlights what makes waste data unique.

Key words:
data anonymization; waste management; PAYT; differential privacy; privacy by design

JEL Classification Q53, K32, O33 https://doi.org/10.52665/ser20260106

INTRODUCTION

Waste management is undergoing rapid digitalization. Modern systems rely on RFID chips embedded in collection bins, GPS tracking of vehicles, fill-level sensors in smart containers, and weight-based PAYT billing to optimize collection logistics and enforce producer-responsibility obligations (Brighente et al., 2023). These technologies generate fine-grained data streams that are operationally indispensable but simultaneously encode sensitive information about individuals, businesses, and public infrastructure.

The privacy implications are broader than commonly assumed. A PAYT record links a specific bin chip to a household and, when combined with timestamps, reveals daily routines, holiday absences, dietary habits, and health indicators through pharmaceutical packaging (Brighente et al., 2023; Sampaio et al., 2023). Industrial waste data disclose production volumes and supply-chain relationships that companies classify as trade secrets. GPS logs of collection vehicles expose the operational topology of private businesses.

Despite this, waste management remains an underexplored domain in the data-privacy literature. Existing work either treats it as a peripheral use case of broader smart-city frameworks (Sampaio et al., 2023; Liu et al., 2017) or addresses IoT security threats at a hardware level (Brighente et al., 2023). A systematic, stakeholder-grounded treatment of anonymization requirements, applicable legal obligations, and AI-driven technical solutions in the waste sector is absent.

This paper fills that gap with the following contributions: (i) a structured analysis of anonymization needs for all major stakeholder groups; (ii) a review of legal obligations; (iii) an evaluation of classical and AI-driven anonymization techniques calibrated to waste-management data types; (iv) a five-layer

anonymization workflow derived from operational practice at Slovak waste-collection operators; and (v) a comparative analysis against water, heat, and telecommunications utilities.

2. Data in Waste Management and Privacy Challenges

2.1 Types of Collected Data

Waste-management information systems handle three categories of data, each with a distinct privacy profile (Brighente et al., 2023; Sampaio et al., 2023).

Static infrastructure data describe the physical collection network: container locations, bin capacities, and cadastral ownership records. Although relatively low-risk in isolation, static data enable household-level inference when combined with public registers.

Dynamic operational data are generated afresh for each collection event: RFID chip reads, container weights, GPS coordinates and routes of collection vehicles, precise timestamps, and fill-level sensor readings. A sequence of RFID reads with precise timestamps is sufficient to uniquely identify a household and reconstruct its daily routine, occupancy pattern, and consumption habits.

Producer data link waste quantities to their origin. For citizens, this means PAYT contracts and billing records. For businesses it means waste declarations and reports and carrier documents that can reveal production volumes and supply-chain relationships. In Slovakia, the split between industrial and municipal waste is approximately 80% to 20% by mass—industry produces roughly 10 million tonnes per year compared to 2.6–2.7 million tonnes of municipal waste—yet it is municipal data that create the greatest privacy challenges (Slovak Environmental Agency, 2023).

2.2 Stakeholder Anonymization Requirements

Data anonymization in waste management affects waste record-keeping, inspection, infrastructure planning, and public oversight. Each stakeholder has different motivations: municipalities and collection companies need data granularity; the state and analysts need aggregation; citizens and businesses protect privacy; technology providers implement technical solutions; and PROs require data accuracy to meet their legal obligations. Table 1 summarises the key tensions.

Table 1: Stakeholder Anonymization Requirements in Waste Management

Stakeholder	Role	Anonymization Need	Key Conflict
Municipality / City	System organizer, planner	Household-level data for planning; anonymized for public reports	Accuracy vs. citizen privacy
Citizen	Primary waste producer (PAYT payer)	Bin chip ID linked to billing only; no lifestyle profiling; right to be forgotten	PAYT enforcement vs. behavioural exposure
Business	Industrial/commercial producer	Production volumes hidden as trade secrets; ESG reporting preserved	Regulatory transparency vs. competitive exposure
Collection company	Operational collector, RFID records	Full detail for invoicing; anonymized before sharing	Liability reduction vs. reporting obligations
PRO (OZV)	Producer-responsibility fulfilment, audit	Pseudonymized material flows for audit; market shares hidden	Audit accuracy vs. B2B confidentiality
State / Regulator	Legislation, Eurostat reporting	Municipal-level aggregates;	Statistical quality vs. GDPR minimization
Inspection authority	Compliance verification, GDPR oversight	Pseudonymization with audit trail; DPIA for new tech	Control access vs. lawful processing
Technology provider	ERP, sensors, smart bins	Privacy-by-design at edge; PII separated from operational data	Scalability vs. bespoke municipal standards

Waste-collection companies operate at the intersection of all stakeholder interests: they must maintain identifiable records for invoicing (RFID chip → customer contract), yet share anonymized statistics with municipalities and PROs. Employee telemetry from vehicle tracking systems adds a further dimension: telematics data must be anonymized for general fleet analytics to avoid conflicts with labour law (EDPB, 2020).

PROs – Producer Responsibility Organisations (in Slovakia termed OZV) occupy a structurally unique position: their auditing function requires access to collection records, but they do not want to become controllers of citizen personal data. Anonymization at the household level lets them verify that a collection route was completed without ever knowing which household produced what volume. Conversely, their B2B data must remain confidential to prevent competitors from inferring market shares (Sampaio et al., 2023).

3. LEGAL AND REGULATORY FRAMEWORK

Anonymization is frequently discussed in the context of the General Data Protection Regulation (Regulation (EU) 2016/679) (GDPR), where it functions as a key mechanism for excluding data from the scope of personal data protection law. As clarified in Recital 26 GDPR, data that have been rendered truly anonymous are no longer considered personal data, whereas pseudonymized data remain subject to the full set of regulatory obligations. This distinction provides a central legal incentive for the implementation of anonymization techniques in data-driven systems.

However, in the context of waste management, a strictly GDPR-centric understanding of anonymization is inherently limited. Waste management systems generate and process heterogeneous datasets that, from a legal perspective, extend beyond personal data and may simultaneously encompass multiple categories of legally relevant information. These include, in particular, (i) personal data related to individuals (e.g., household waste production patterns), (ii) commercially sensitive information concerning business entities (e.g., industrial waste composition or volume), and (iii) operational or infrastructural data (e.g., collection routes or facility capacities).

From a legal perspective, anonymization should therefore be understood as a cross-cutting risk mitigation mechanism aimed at preventing the identification of legally protected interests, rather than merely the identification of natural persons. While GDPR focuses on the identifiability of individuals, other legal regimes—such as trade secret protection, contractual confidentiality obligations, or sector-specific regulation—may apply even where data no longer qualifies as personal data.

This broader understanding reveals a potential misalignment between technical and legal approaches to anonymization. Technical implementations often define anonymization in terms of the removal or transformation of direct identifiers, or through aggregation techniques. However, such measures may be insufficient from a legal standpoint if the resulting dataset still enables the inference of commercially sensitive information or reveals strategic or operational characteristics of specific entities.

Consequently, anonymization in waste management should be assessed in a multi-layered manner, taking into account not only the risk of re-identification of individuals, but also the potential for indirect identification or inference affecting corporate actors and critical infrastructure.

In addition, PAYT systems, which enable the identification of individual households, introduce specific privacy and societal risks. Such systems may facilitate detailed lifestyle profiling: patterns in pharmaceutical packaging may reveal health conditions; consumption habits may be inferred from waste composition; and temporal disposal patterns may disclose occupancy rhythms, including periods of absence. Furthermore, residents of lower-income neighborhoods may face an increased risk of stigmatization where waste-related performance indicators, such as recycling rates, are published at a granular, street-level resolution without adequate aggregation.

Accordingly, the adequacy of anonymization measures in this context must be assessed not only against the risk of individual re-identification, but also in light of their potential to enable inference,

profiling, and socially detrimental outcomes, thereby requiring evaluation across multiple legal and regulatory frameworks rather than exclusively under GDPR criteria.

4. ANONYMIZATION METHODS FOR WASTE MANAGEMENT DATA

Anonymization techniques fall into classical statistical methods applicable to structured tabular records, and AI-driven approaches that extend anonymization to unstructured documents, spatial data, and video streams. Both categories are required in waste management; their combination within a layered architecture is the recommended approach.

4.1 Classical Statistical Methods

Generalization and suppression reduce the precision of attribute values (e.g., exact address → postal-code zone) or remove them entirely. Applied to GPS coordinates, generalization to street-segment level eliminates household-level identifiability while preserving spatial density information needed for route planning.

Pseudonymization and tokenization replace real identifiers with cryptographically generated tokens. In waste-collection practice, the bin chip ID and customer contract number are the primary identifiers: at the moment of collection, the vehicle system replaces the real chip ID with an HMAC-SHA256 token using a daily-rotating key. Only the billing department retains the mapping table; all other system modules (dispatching, analytics, reporting) operate exclusively on tokens. This is operationally non-negotiable—collection operators cannot function without linking collections to customers for invoicing—but full anonymization of this link is possible once the billing purpose is fulfilled (Brighente et al., 2023).

k-Anonymity (Sweeney, 2002) guarantees that each published record is indistinguishable from at least $k-1$ others on quasi-identifier attributes. Applied to street-level waste statistics, a rule of $k \geq 5$ means data for a street with fewer than five households are merged with an adjacent segment before publication. This directly implements the operational requirement of collection operators who, when reporting to municipalities or PROs, must ensure that aggregated tonnage figures cannot be traced to individual addresses. k-Anonymity alone is vulnerable to homogeneity attacks when sensitive attribute values within a group are uniform; **l-diversity** and **t-closeness** extensions address this limitation.

Temporal generalization (time masking) addresses the fact that a precise collection timestamp exposes a household's daily routine. Rounding timestamps to one-hour slots is sufficient for route efficiency statistics while preventing behavioural inference.

4.2 AI-Driven Anonymization Methods

Classical methods are insufficient for unstructured data sources prevalent in waste management: scanned carrier documents, free-text ERP fields, and video streams from vehicle-mounted cameras.

To illustrate: a scanned delivery note accompanying a waste shipment may contain the driver's name, the client's company name, and a GPS-tagged pickup address. A human clerk would redact these manually; the AI pipeline described below performs the same task automatically, at scale, and without human access to the underlying data.

Differential Privacy (DP) (Dwork et al., 2006) provides a mathematically rigorous guarantee by injecting calibrated Laplace noise into query results. In waste management, DP is applied to aggregate reporting: recycling-rate statistics exported to municipalities or open-data portals are protected with $\varepsilon = 0.5$ noise, preserving aggregate accuracy while preventing individual inference. The same Laplace mechanism provides practical guarantees for location and mobility data (Duchi et al., 2013), making it directly applicable to GPS trajectory records from collection vehicles.

NLP/NER-based document redaction uses pre-trained transformer models (BERT, RoBERTa) fine-tuned for Named Entity Recognition to automatically detect and redact personal spans—person names, company names, addresses, VAT numbers, and GPS coordinates embedded in text—replacing them with category placeholders such as [PERSON] or [ORG] (Kaur et al., 2025). Redaction can replace identified

spans with category labels or synthetic substitutes generated by language models, preserving document readability for downstream analysis. This technique directly automates the manual export process currently used by collection operators when preparing data for commercial presentations or research handovers.

OCR integration enables retroactive anonymization of scanned paper documents (weighbridge slips, carrier documents, historical waste declarations) via an OCR-to-NER pipeline: Tesseract or Azure Document Intelligence converts scanned images to machine-readable text, a ByT5-based spell-correction module reduces OCR noise, and the NER redactor processes the cleaned text. Quality of anonymization depends critically on OCR accuracy; post-correction is therefore recommended before NER processing (Kaur et al., 2025; Brighente et al., 2023).

Computer vision anonymizes video streams from vehicle-mounted cameras in real time. A YOLOv8-based detection pipeline blurs faces and license plates before frames are encoded and transmitted, implementing Privacy by Design at the edge (Zhang et al., 2021; Angus and Duan, 2022). For applications requiring higher visual fidelity, GAN-based face replacement (CIAGAN; Maximov et al., 2020) preserves scene utility while eliminating biometric identifiability.

Spatial fuzzing applies a Laplace-distributed coordinate offset of 20–50 m to GPS points before publication, preserving spatial density patterns for route optimization while preventing point-level re-identification. Two complementary techniques are applied: (a) *aggregation to polygons*—precise coordinates are replaced by street-segment or neighborhood-zone codes in all external reporting; (b) *coordinate fuzzing*—a random Laplace offset is added before publication. Collection operators already practice a form of this by publishing route data aggregated to street level rather than individual stop coordinates (Brighente et al., 2023; Sampaio et al., 2023).

Vision-Language Models (VLMs) such as LLaVA and Llama 3.2 Vision advance document anonymization by processing scanned document images end-to-end, simultaneously interpreting layout and content without a separate OCR stage. This context-awareness is critical for complex waste-sector forms where positional semantics determine sensitivity. **A strict requirement is that VLMs are deployed exclusively as locally-hosted models** (e.g., via Ollama[1] or llama.cpp[2]): sending waste documents to cloud-based APIs constitutes a transfer of personal data under GDPR Article 28 and, where the provider is outside the EEA, a cross-border transfer under Chapter V.

Agentic LLM pipelines combine a locally-hosted LLM (e.g., Mistral 7B, Qwen2.5) with specialist tools—NER redactor, k-anonymity checker, spatial aggregator, audit logger—orchestrated via a ReAct (Reason-Act-Observe) loop. Given a document or dataset, the agent autonomously: (1) classifies the data type and applicable sensitivity level; (2) selects and invokes the appropriate anonymization tool; (3) verifies the output against re-identification criteria; and (4) iterates if residual risk is detected, logging each step for the GDPR audit trail. This replaces the labour-intensive manual export process used by collection operators. The entire pipeline runs on-premise and is auditable by the Data Protection Authority without exposing data to external parties.

Synthetic data generation produces statistically equivalent artificial datasets containing no real individuals. CTGAN and TVAE generative models trained on historical waste data—weights, timestamps, GPS zones—learn the underlying distributions and inter-variable correlations and sample new records that preserve aggregate statistics without retaining any original row (Bertino and Sandhu, 2005). For waste management, synthetic datasets enable municipalities and researchers to train route-optimization or fill-level prediction models without access to citizen PAYT data, and allow operators to demonstrate system capabilities in commercial presentations without exposing real customer or geographic information. Properly generated synthetic data carry no GDPR obligations, as they do not qualify as personal data.

[1] https://ollama.com

[2] https://github.com/ggml-org/llama.cpp

Federated learning (FL) enables collaborative AI model training across multiple municipalities without any raw data leaving the local environment. Each participant trains a local model update on their own dataset; only the model gradients (not the data) are aggregated by a central coordinator to produce an improved global model. For waste management, FL allows a shared fill-level-prediction or collection-route model to be trained across multiple Slovak municipalities without any city exchanging citizen-level PAYT records. When combined with differential privacy applied to the gradients (DP-SGD), FL provides a mathematically bounded privacy guarantee even against a malicious aggregator. The coordinator server never holds raw data, eliminating the primary GDPR data-controller liability from the aggregation step.

Note: Methods based on AI model inference (VLMs, agentic pipelines) must be deployed exclusively on local infrastructure. Cloud-hosted model APIs introduce GDPR transfer risk and audit opacity, making them incompatible with Privacy by Design (Art. 25 GDPR).

4.3 Method-to-Data-Type Mapping

Table 2 maps the waste-management data types to recommended anonymization methods, balancing privacy risk against operational constraints.

Table 2: Recommended Anonymization Methods by Waste-Management Data Type

Data Type	Privacy Risk	Recommended Method(s)	Deployment Constraint
Bin chip ID (RFID)	High – household link	Tokenization (HMAC-SHA256, daily key)	Billing module retains mapping; all others use tokens only
GPS collection point	High – re-id via cadastre	Spatial aggregation (street/zone) + Laplace fuzzing (20–50 m)	Route optimization requires density, not point precision
Collection timestamp	Medium – daily routine	Time-slot generalization (1-hour bins)	Schedule analytics need slot-level precision
Waste weight per bin	Medium – PAYT link	k-Anonymity ($k \geq 5$) per street segment; DP noise for open data	Internal invoicing requires exact weight
Carrier / declaration doc.	High – names, addresses, VAT	OCR → NER (BERT) or VLM end-to-end (LLaVA, local)	All inference on-premise; audit log required
Vehicle video stream	High – faces, licence plates	YOLOv8 edge detection + Gaussian blur / CIAGAN	Blurring on-vehicle before transmission
ERP free-text fields	Variable	NER fine-tuned; agentic LLM for context-aware redaction	Local LLM only; replaces manual export
Historical tabular records	Medium – aggregate re-id	Synthetic data (CTGAN / TVAE) for research / demo handover	Generator trained on-premise; output freely shareable
Cross-municipal AI training	High – citizen PAYT	Federated Learning + DP-SGD on gradients	Raw data never leave local node

5. CASE STUDY: ANONYMIZATION WORKFLOW FOR WASTE-COLLECTION OPERATORS

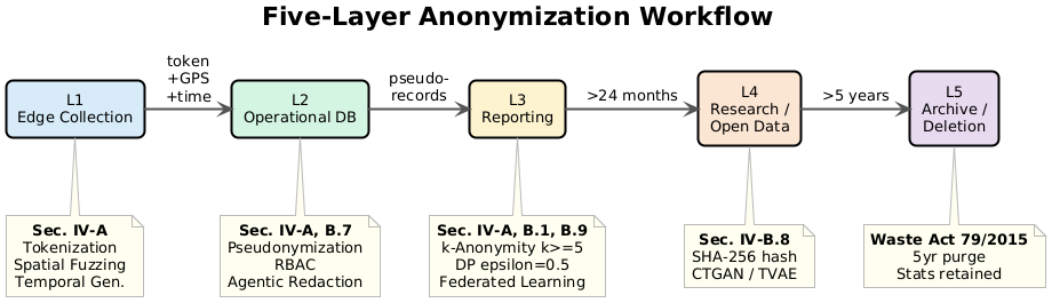
Waste-collection companies are simultaneously data controllers, data processors (acting on behalf of municipalities), and data subjects (employee telemetry). This section demonstrates how the methods described in Section 4 are composed into an integrated, five-layer workflow derived from operational

requirements at Slovak collection operators including Marius Pedersen, BRANTNER Slovakia, OLO, KOSIT, FCC Slovensko, and AVE SK, which together cover the majority of the Slovak municipal waste-collection market (Slovak Environmental Agency, 2023).

5.1 Five-Layer Anonymization Architecture

The architecture separates data by purpose and applies progressively stronger anonymization as data move away from their operational origin. Fig. 1 shows the data flow; each layer references the Section 4 methods it employs.

Figure 1: Five-Layer Anonymization Architecture for Waste-Collection Operators.



The five layers are as follows:

Layer 1 – Edge Collection (Sec. 4.1: Tokenization, Spatial Fuzzing, Temporal Gen.): The RFID reader on the vehicle replaces each bin chip ID with an HMAC-SHA256 token (daily-rotating key) before any data leave the vehicle. GPS coordinates are fuzzed with a Laplace offset of 20–50 m and timestamps are rounded to 5-minute slots. Raw identifiers never transit the network.

Layer 2 – Operational Database (Sec. 4.1, 4.2: Pseudonymization, RBAC, Agentic Redaction): The central ERP stores pseudonymized records; only billing staff hold the token-to-customer mapping. Incoming scanned carrier documents are routed through the on-premise agentic anonymization pipeline (Sec. 4.2) before storage, replacing manual redaction.

Layer 3 – Reporting to Municipalities and PROs (Sec. 4.1, 4.2: k-Anonymity, DP, FL): Records are aggregated to street-segment level with $k \geq 5$. Differential privacy noise ($\varepsilon = 0.5$, Laplace mechanism) is added to weight totals. For cross-municipal model training, federated learning with DP-SGD is applied so that raw records never leave the operator's server.

Layer 4 – Research and Open Data (Sec. 4.2: Full Anonymization, Synthetic Data): Records older than 24 months are fully anonymized: tokens replaced with non-reversible SHA-256 hashes, temporal precision reduced to month-year, spatial precision to neighborhood level. For research datasets, CTGAN/TVAE-based synthetic data generation produces GDPR-free datasets preserving aggregate distributions.

Layer 5 – Archive and Deletion (Waste Act No. 79/2015): Records older than the statutory five-year retention period are automatically purged. Aggregated statistical records (no personal data) are retained indefinitely, preserving institutional memory of waste flows.

This architecture operationalizes GDPR Articles 5, 17, 25, and 35. In the event of a data breach, anonymized tokens at Layers 2–4 carry no notification obligation, transforming compliance risk into a manageable technical property (Brighente et al., 2023; Sampaio et al., 2023).

5.2 Vehicle Camera Pipeline

This pipeline instantiates the computer-vision methods of Section 4.2 in an operational on-vehicle context. YOLOv8-nano detects faces and license plates at ≈25 fps; a 31×31 Gaussian kernel blurs detected regions before frame encoding. The anonymized frame—not the raw video—reaches the central server. For contamination-detection applications, the CIAGAN face-replacement method (Maximov et al., 2020) is

applied instead of blurring. VLM-based post-processing of selected frames is executed on-premise via a locally-hosted model.

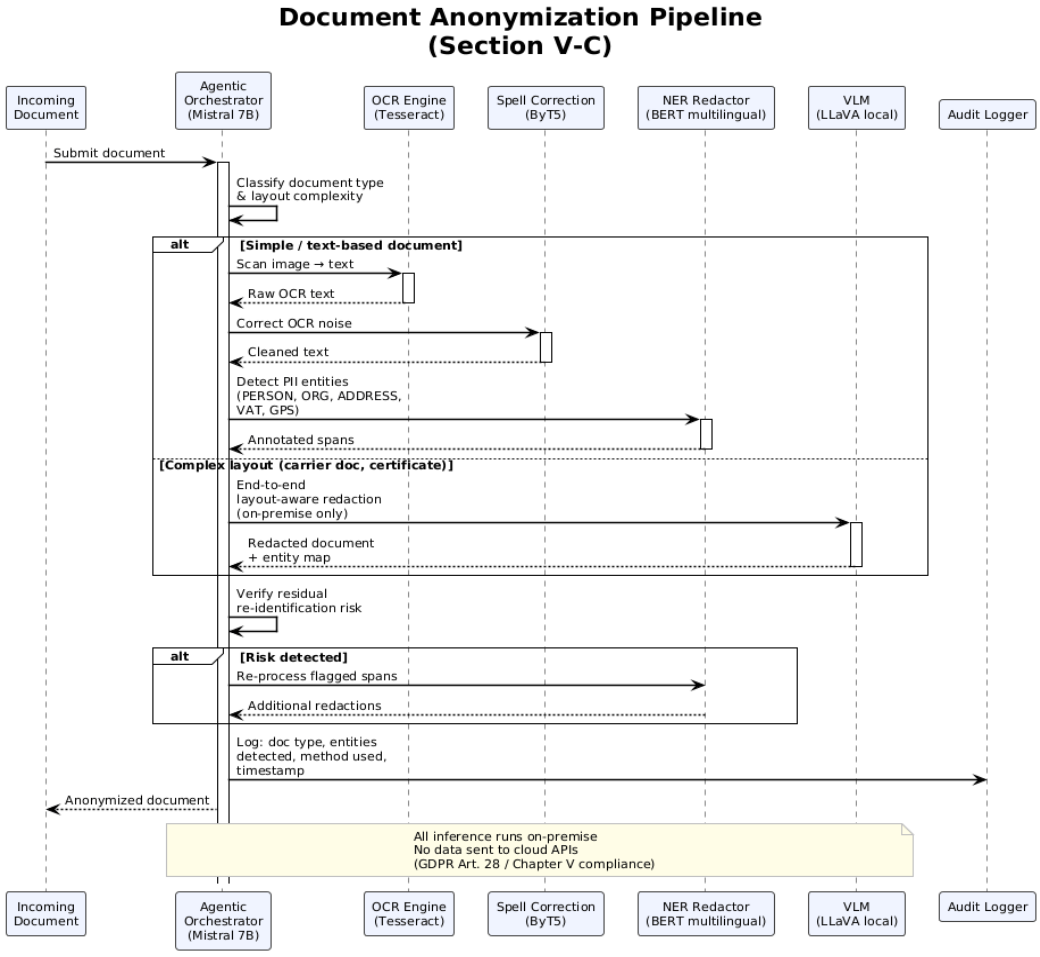
In practice, the pipeline runs on an embedded GPU module (e.g., NVIDIA Jetson Orin) mounted in the collection vehicle. Processing latency stays below 40 ms per frame, ensuring real-time operation without buffering raw footage. Anonymized frames are stored locally for 24 hours for operational review and then purged automatically, in line with the data-minimisation principle of Article 5(1)(c) GDPR.

5.3 Document Anonymization Pipeline

In simple terms: every document entering the system is automatically checked for personal data and sensitive identifiers, which are replaced by neutral placeholders before the document is stored or shared.

Fig. 2 shows the document anonymization sequence. Legacy scanned documents follow the OCR→NER path (Tesseract + ByT5 spell correction + BERT-base-multilingual NER). New documents with complex layouts (multi-party carrier forms, weighbridge certificates) are processed end-to-end by a locally-hosted VLM (LLaVA). Both paths are orchestrated by the agentic pipeline, which classifies incoming documents, selects the appropriate path, verifies residual re-identification risk, and logs each decision for the GDPR audit trail.

Figure 2: Document Anonymization Pipeline: OCR/NER path for legacy documents and VLM end-to-end path for complex layouts, orchestrated by an on-premise agentic system.



6. Comparison with Other Regulated Utility Sectors

Waste management shares the regulated-utility context with water supply, district heating, and telecommunications. Table 3 summarises the key dimensions of comparison.

Table 3: Anonymization Comparison Across Regulated Utility Sectors

Dimension	Waste	Water (URSO)	Heat / Energy	Telecommunications
Data cadence	Episodic (collection events, weekly)	Continuous (smart meter, real-time)	Continuous (smart meter, seasonal)	Real-time (CDR, location, browsing)
What data reveal	Lifestyle, health indicators, occupancy	Occupancy, health (nightly water draws)	Economic vulnerability, occupancy	Location, social graph, interests
Re-id risk	Medium – RFID + cadastre + timestamp	High – flow curves near-biometric	High – seasonal correlation	Very high – mobility traces
Primary method	Tokenization, k-anonymity, DP, spatial fuzzing	Flow-curve perturbation, DP	Zone-level aggregation	DP (trajectory), CDR aggregation
Regulation	GDPR + Waste Act + WFD	GDPR + Water Act + URSO	GDPR + Energy Act	GDPR + ePrivacy + NIS2
Unique challenge	Physical dumpster diving bypasses digital anonymization	Leak detection needs sub-hourly precision	Seasonal correlation degrades anonymization	Re-id from mobility even after DP

The key differentiator of waste data is its physical tangibility: digital anonymization of database records does not prevent inference from direct inspection of physical waste (dumpster-diving attacks). This means digital anonymization must be complemented by physical-security controls—a challenge with no parallel in digital utility sectors (Brighente et al., 2023; Sampaio et al., 2023).

Water utilities (URSO-regulated in Slovakia) face the most analogous challenge: high-frequency smart-meter data are effectively a biometric signature of a household. Unlike waste, water consumption is continuous—a single day's water-draw curve reveals the number of occupants, nightly health conditions (nocturnal polyuria), and when the apartment is empty. Anonymization must therefore protect flow curves, not just totals, while preserving sufficient precision for network-leak detection. The recommended approach—trusted execution environments running leak-detection algorithms on non-exported raw data, with only aggregated daily totals published—is directly applicable to future high-frequency PAYT systems that weigh bins at every emptying (Sampaio et al., 2023; Brighente et al., 2023).

Heat and energy suppliers present a different challenge: low heating consumption in winter can signal energy poverty or an empty apartment (a burglary risk). Anonymization must suppress socio-economic inference while satisfying energy-efficiency regulations. The seasonal correlation of heat data with weather patterns also complicates anonymization: residualizing out weather effects can re-expose individual consumption anomalies (Sampaio et al., 2023; Liu et al., 2017).

Telecommunications operators represent the most complex anonymization challenge. Mobility traces and call-detail records (CDRs) enable re-identification even after differential privacy is applied, because trajectory data contain unique spatio-temporal fingerprints (Liu et al., 2017). The key difference from waste data is *dynamic trajectories vs. static points*: waste anonymization deals primarily with fixed container locations and scheduled collection events, making it technically far more tractable than telco. The unique challenge with no parallel in digital utility sectors is physical dumpster diving, which requires physical-security controls as a necessary complement to digital anonymization (Brighente et al., 2023; Liu et al., 2017; EDPB, 2020).

CONCLUSION

This paper has presented a systematic, stakeholder-grounded analysis of data anonymization in waste management. Three principal findings emerge.

First, waste-management data are more privacy-sensitive than the sector traditionally acknowledges. The combination of RFID identifiers, GPS coordinates, and precise timestamps uniquely identifies households and exposes behavioural, health, and economic information. Industrial waste data constitute trade secrets requiring protection under commercial law in addition to GDPR. The multi-stakeholder structure creates irreconcilable tensions that no single technique resolves.

Second, AI-driven methods substantially extend classical anonymization to the unstructured data types prevalent in waste management. NLP/NER pipelines with OCR integration automate manual document-redaction. Computer-vision blurring and GAN-based face replacement enable Privacy by Design compliance for vehicle camera systems. VLMs enable context-aware end-to-end document anonymization; agentic LLM pipelines orchestrate the full workflow with a logged audit trail; synthetic data generation produces GDPR-free datasets; and federated learning enables cross-municipal model training without raw-data sharing. Together, these techniques address all nine data types identified in the operational taxonomy (Table 2). A critical deployment requirement is that all AI inference runs on local infrastructure—not cloud APIs.

Third, the five-layer workflow—edge pseudonymization, role-controlled operational database, k-anonymous reporting, DP-protected open data, and scheduled archive purge—operationalizes GDPR Articles 5, 17, 25, and 35 in a sector-specific manner. Its most important practical benefit is liability reduction: anonymized tokens released in a breach carry no GDPR notification obligation, transforming risky data into safe business assets without sacrificing analytical value.

From a practical standpoint, several challenges remain. (1) The diversity of legacy document formats in waste management makes it difficult to deploy a single NER model with consistently high recall across all operators. (2) The absence of labelled waste-sector datasets limits the benchmarking of anonymization quality. (3) Physical re-identification through direct waste inspection has no technical countermeasure — it requires organisational and legal controls that fall outside the scope of data anonymization alone.

Compared to water and energy utilities, waste management benefits from episodic (rather than continuous) data cadence, which simplifies anonymization. Compared to telecommunications, waste deals with fixed points rather than dynamic trajectories, making re-identification technically more tractable. As noted in Section 6, the absence of a purely digital countermeasure to physical waste inspection remains the sector-specific open problem.

Future work will focus on: quantifying re-identification risk on real Slovak waste-management datasets using membership-inference attacks; developing a labelled waste-sector NER corpus for benchmarking document-redaction models; and evaluating federated learning for cross-municipal model training without raw-data sharing.

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Gender - Balanced Representation in Executive Management

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Abstract

The European Union has consistently promoted, alongside with other measures, ensuring equal treatment of men and women in practice in employment, work and pay. The principle of equal treatment and equal opportunities between women and men, as well as employment conditions and career opportunities, are the key areas of activities of the European Union. To properly coordinate and implement gender equality policy, it has adopted several legal acts which the Member States must transpose into their national legislation. This legislation, adopted at European Union level, contributes to improving gender balance in the executive positions. The paper is focused on the analysis of the current state of elimination of gender differences among directors of listed companies within the European Economic Area with special focus on Slovakia. It is a matter of fact that in present, women are scarcely represented in senior management positions in private companies and public institutions. The objectives are to highlight the promotion of career development of women at all levels of management and the economic and social responsibility of such companies. For the preparation of this article, we have applied text analysis and description methodology. The methodological tools include desk research with emphasis on analysis of the documents and EU laws as well as the results of several reports.

Key words:
gender balance, corporate boards, woman, directive, EU law

JEL Classification K15, K 31, K 36 https://doi.org/10.52665/ser20260107

INTRODUCTION

The European Union as well as many other international organisations consider gender equality to be a core value, as equality between men and women is a fundamental human right without which it is impossible to build fair and democratic society[3]. The International Labour Organisation is a major promoter of gender equality in the labour market. The United Nations has also adopted numerous conventions aimed at improving the status of women in society. The European Union's current gender equality policy is based on a human rights-based approach to men and women. In striving for a Union of equality, it is key that equality and non-discrimination are respected throughout the EU and that citizens can benefit from the same level of protection of their rights wherever they live in the EU.[4]

A universal determinant for the elimination of inequalities in working and private life is the elimination of all forms of discrimination. Equality between men and women is also proving beneficial for economic growth; as high female employment is important for sustainable economic growth, social stability and a socially fair state. We are of the opinion that gender equality is not only a matter of a democratic society and social justice, but also of a smart economy. The Union has a large pool of highly

[3] Article 11 of the United Nations Convention of 18 December 1979 on the Elimination of All Forms of Discrimination against Women, which all Member States have ratified, provides that States Parties are to take all appropriate measures to ensure, inter alia, the right to equal remuneration, including benefits, and to equal treatment in respect of work of equal value, as well as equality of treatment in the evaluation of the quality of work.

[4] European Commission (2022) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Enforcing EU law for a Europe that delivers COM/2022/518 final

qualified women, which is constantly growing as evidenced by the fact that 60 % of university graduates are female.[5] That is why, we believe that business companies should exploit this potential and shape business models where women are also represented in the top management bodies. Women's talents and a greater presence of women at all levels of corporate management can also have a greater positive impact on closing the gender gap in employment and the gender pay gap for employees for equal work. Gender balance among business executives who carry out day-to-day management tasks should be part of the corporate culture and a universal principle for responsible business doing. Globally, women hold just 28.2% of management positions in the workplace.[4] Data show that women are underrepresented in management positions. In a set of G20 and guest countries with available data, just under 30 % of middle and senior management positions are occupied by women with considerable variation by region (International Labour Organisation, 2020)[6].

LITERATURE OVERVIEW

Gender equality means an equal visibility, empowerment and participation of both sexes in all spheres of public and private life. Gender equality is the opposite of gender inequality, not of gender difference, and aims to promote the full participation of women and men in society.[7] In this context, gender equality can be understood as a universal principle of social rights. Equality between women and men is an economic investment in the future, which also contributes to the economic growth of society in several ways.[8]

A fairly comprehensive explanation of gender balance is provided by the Glossary of Terms and Concepts (UNICEF, 2017).“ *Gender balance- this is a human resource issue calling for equal participation of women and men in all areas of work (international and national staff at all levels, including at senior positions) and in programmes that agencies initiate or support (e.g. food distribution programmes). Achieving a balance in staffing patterns and creating a working environment that is conducive to a diverse workforce improves the overall effectiveness of our policies and programmes and will enhance agencies' capacity to better serve the entire population.*[9]“ This interpretation of the concept of gender balance is based on the equal status of men and women in employment relations and on equality of opportunity. Gender equality cannot be achieved by anti-discrimination policy alone but requires measures to promote harmonious coexistence and balanced participation of men and women in society. Gender equality cannot be achieved by an anti-discrimination policy alone but requires measures to promote harmonious co-existence and balanced participation by men and women within society.[10]

Gender diversity in decision making has traditionally been measured by the proportion of women in managerial positions. It is nowadays a fact that women are scarcely represented in senior management positions in private companies and public institutions. The Global Gender Gap Index annually benchmarks the current state and evolution of gender parity across four key dimensions: economic participation and opportunity, educational attainment, health and survival, and political empowerment. European economies

[5] Para 16 Directive (EU) 2022/2381 of the European Parliament and of the Council of 23 November 2022 on improving the gender balance among directors of listed companies and related measures http://data.europa.eu/eli/dir/2022/2381/oj

[6] International Labour Organisation, 2020. https://www.ilo.org/publications/annual-report-2020

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[10] Recital 11Regulation (EC) No 1922/2006 of the European Parliament and of the Council of 20 December 2006 on establishing a European Institute for Gender Equality OJ L 403, 30.12.2006 http://data.europa.eu/eli/add/2006/1922/oj

occupy seven spots out of the global top 10. Iceland (93.5%) is again ranked 1st , Finland 2nd (87.5%), Norway 3rd (87.5%), Sweden 5th (81.6%), Germany 7th (81%), Ireland 9th (80.2%) and Spain 10th (79.7%) and Slovakia (68.7%). With 70.2 points out of 100, the European Union still has much to do to reach gender equality. The EU's current score represents a moderate improvement of 1.6 points compared with the previous edition of the Index – the highest year-on-year rise since the first edition of the Index in 2013. The increase in the EU's score since 2020 is mainly due to progress in gender equality in the domains of time (+ 3.6 points) and work (+ 2.1 points). Since 2010, the EU's score has increased by 7.1 points, primarily driven by advances in the domain of power (+ 17.2 points).[11]

Economic share of members of boards in largest quoted companies, supervisory board or board of directors is 33% in 2010 and change represents 67% in 2023 at EU level. A corporate board of a listed company is balanced when each gender makes up at least 40% of its composition[12].

As of early 2025 the overall average share of women on the boards of the largest listed companies in the EU has risen to 34%.

Globally, women hold about 24 per cent of managerial positions in 2023.The under-representation of women in top-positions in business life is receiving increasing attention worldwide. In 2024 data shows that women's workforce representation remains below men's across nearly every industry and economy, with women accounting for 42% of the global workforce and 31.7% of senior leaders (Global Gender Gap Report 2024).

Women's opportunities to hold leadership positions in organisations are restricted due to the glass ceiling, which contributes to the perpetuation of gender inequalities within organisations. According to social closure theory (Tomaskovic-Devey 1993), males monopolise advantages and limit women's opportunities for promotion, leading to a process of subordination.

As far as the gender wage disparity is concerned, it persists throughout Europe. According to Eurostat (2023), the average gender wage gap for the European Union (EU27) has been narrowed, falling from 14.5% in 2015 to 14.4% in 2018 and 12.7% in 2021.

Attention has mostly been directed toward the lack of women on corporate boards (e.g. Gabaldon et al. 2016; Seierstad et al. 2015; Terjesen, Sealy, and Singh 2009). However, the lack of gender balance in top-executive positions has also been addressed (e.g. Bertrand et al. 2014; Cook and Glass 2014; Gupta and Raman 2014). The gender imbalance stands in contrast to women's educational attainment and their general labour-market participation. Although gender imbalance among key decision-makers is widespread, the largest gap is found within the business sector (e.g. Davidson and Burke 2024). It has been proven that women have less experience than men in senior management positions in general and in line management, and in particular profit and loss responsibility (Halrynjo and Teigen 2024). The reasons therefore vary in the literature. Gender inequities at work are also affected by labour code, human resource practices and as well as by the gender inequities at a societal level (Hideg and Krstic, 2021).

Some research studies highlight gender differences in values, attitudes, and gender identities. One explanation is women's lack of interest in management, which may come from travel demands and competition for promotions (Matsa and Miller 2011). The work–life conflict could include gender differences in experienced levels of stress and spillover, as well as gender differences in actual division of family responsibilities (Gabaldon et al. 2016).

METHODOLOGY

The aim of the article is to highlight the current policy developments in the application of the principle of equal opportunities and equal treatment of men and women in matters of employment and occupation. In the framework of the examination of the topic we have focused on the new legal framework of balanced representation of women and men in the management bodies of listed companies. We compared listed and unlisted companies using a comparative method. The object of the research is the legal relations establishing the obligation for companies to have gender representation in their management bodies. The

[11] The Global Gender Gap Index 2025 https://www.weforum.org/publications/global-gender-gap-report-2025/
[12] Gender balance in business and finance, European Institute for Gender Equality doi:10.2839/788367

object of the research is gender balance, i.e. that members of the under-represented gender hold at least 40 per cent of non-executive management positions or hold at least 33 per cent of all management positions.

We used the Directive (EU) 2022/2381[13] and the corresponding Slovak legislation, which is in the process of approval, as the basic source of research. Secondary analysis of data from the Commercial Register was used to show the representation of men and women in the bodies of companies operating in Slovakia. We pointed out the gender imbalance in the governing bodies of selected companies that have been operating on the Slovak market for a long time. We identified the obligations of companies that must have a balanced representation of women and men in the management bodies of listed companies. We paid special attention to summarizing the results of the research.

EU legal framework

Since its establishment, the European Union (then European Communities) has emphasised equal treatment and gender equality. Since its inception, the European Union (then the European Communities) has emphasised equal treatment and gender equality. This principle is included in numerous provisions in the primary legislation of the European Union, in secondary acts and in other instruments such as the European Pillar of Social Rights[14]. The EU legislation has undergone through a scrupulous process of evaluating existing national and EU legislation, consulting the public and assessing the environmental, social and economic impacts.[15]

The issue of gender equality is regulated:

a) in Articles 2 and 3(3) of the Treaty on European Union (enshrine the right to equality between women and men as one of the essential values of the Union)
b) Articles 8, 10, 19, of the Treaty on the Functioning of the European Union (to eliminate inequalities, to promote equality between men and women and to combat discrimination based on sex in all its policies and activities)
c) Articles 153 and 157 of the Treaty on the Functioning of the European Union (the principle of equal pay for male and female workers for equal work or work of equal value is applied)
d) Articles 21 and 23 of the Charter of Fundamental Rights (prohibits any discrimination, inter alia, on the grounds of sex and equality between women and men must be ensured in all areas, including employment, work and pay).

In addition to the European Union's primary legislation, there is a wide range of secondary legislation providing for the elimination of inequalities in public and private life, as well as the elimination of all forms of discrimination. The most relevant secondary legislation at present is Directive (EU) 2022/2381 of the European Parliament and of the Council of 23 November 2022 on improving the gender balance among directors of listed companies and related measures[16] a Directive (EU) 2023/970 of the European Parliament and of the Council of 10 May 2023 to strengthen the application of the principle of equal pay for equal work or work of equal value between men and women through pay transparency and enforcement mechanisms.

[13] European Union (2022) Directive (EU) 2022/2381 of the European Parliament and of the Council of 23 November 2022 on improving the gender balance among directors of listed companies and related measures (Text with EEA relevance). OJ L 315, 7.12.2022, p. 44–59. http://data.europa.eu/eli/dir/2022/2381/oj

[14] European Commission (2021) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions the European pillar of social rights. Action Plan.COM/2021/102 final.

[15] European Commission (2022) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Enforcing EU law for a Europe that delivers COM/2022/518 final

[16] Directive (EU) 2022/2381 of the European Parliament and of the Council of 23 November 2022

These EU secondary legal acts have also had a significant impact on national legal systems, as they had to be transposed into the national legal systems of EU Member States in the required deadline. According to Article 11 of the Directive (EU) 2022/2381 „*Member States shall adopt and publish, by 28 December 2024 the laws, regulations and administrative provisions necessary to comply with this Directive.“* In accordance with Article 34 of the Directive (EU) 2023/970, the directive must be transposed by 7 June 2026 in the Member States. Listed companies carrying out economic activities within the European Economic Area are obliged to take measures to strengthen the participation of women in their top management positions by July 2026. In this context it is necessary that Gender mainstreaming – refers to the systematic integration of the gender perspective into all phases of the preparation, implementation, monitoring and evaluation of policies, regulatory measures and budget spending programmes, with the aim of promoting gender equality and preventing discrimination.[17] It is essential that the adopted legislation is also correctly implemented in practice. In the context of achieving equality between women and men, the decisions of the Court of Justice, which strongly and fundamentally support the implementation of the principle of equality between women and men in practice, cannot be overlooked. The case-law of the Court of Justice has clarified many important aspects of the anti-discrimination directives.[18]

The European Institute for Gender Equality in Vilnius, Lithuania has been set up with a view to properly promoting gender equality and mainstreaming a gender perspective in all policies. The Institute has legal personality and operates independently in the public interest.

The relationship of the Slovak law and the EU law

When joining the European Union, the Slovak Republic undertook to fulfil its obligations arising from its membership of the European Union in good faith. One of the several commitments is the ability to transpose secondary acts into the Slovak legal order and to comply with European Union law. The interrelationship between Union law and the Slovak legal system should be seen not only through the case law of the Court of Justice of the EU, but also through the provisions enshrined in the Constitution of the Slovak Republic. The principle of the primacy of EU law has developed over time by means of the case law (jurisprudence) of the Court of Justice of the European Union. (In *Van Gend en Loos* v *Nederlandse Administratie der Belastingen* Case 26/62[19]).

The primacy of the EU law is not enshrined directly in the EU Treaties, although there is a brief Declaration annexed to the Treaty of Lisbon[20] to this extent. Thus, it was the Court of Justice that gave the Union (then Community) law absolute precedence over national law based on the special nature of Union law compared to ordinary international treaties. A characteristic feature of Union law is its absolute precedence over a conflicting provision of a Member State's law. If Union law is to be effective, it must be correctly and uniformly applied in the territory of the Member States. The principle of primacy contributes to the creation of ‘an ever-closer bond between the peoples of Europe', as set out in the

[17] For more details see, e.g., the World Health Organization definition (https://www.who.int/health-topics/gender#tab=tab_1) European Institute for Gender Equality definition (https://eige.europa.eu/publications/what-gender-mainstreaming). EU Action Plan on Gender Equality

[18] The evolution and impact of the case-law of the Court of Justice of the European Union on Directives 2000/43/EC and 2000/78/EC, ISBN 978-92-79-27787-0 doi: 10.2838/38584 available at https://op.europa.eu/en/publication-detail/-/publication/7a6df925-940f-4823-a37a-3bebd1f55084; Compilation of caselaw on the equality oftreatment between women and men and on non-discrimination in the European Union. Available at: https://op.europa.eu/en/publication-detail/-/publication/e8711e0f-767c-466e-9fae-325dd6d2544f.

[19] CJEU, Judgment of 15 July 1964, Costa v E.N.E.L., Case 6/64

[20] Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community, signed at Lisbon, 13 December 2007.OJ EU C 306, 17.12.2007. Declarations concerning provisions of the Treaties - 17. Declaration concerning primacy

Treaties. The principle of sincere cooperation is enshrined in the second subparagraph of Article 4(3) of the TEU, according to which Member States must take all appropriate general or specific measures to ensure compliance with the obligations arising from the Treaties or from acts of the institutions of the Union. The provision in question explicitly establishes a legal obligation to cooperate with each other in the performance of tasks arising from the Treaties on the basis of the well-known principle of international law *pacta sunt servanda*.

The relationship between EU law and the national laws of the Member States is based on the principle of conferral of powers enshrined in Article 4(1) TEU; since the principle of primacy of EU law applies only within the framework of EU law; the executive and the legislative bodies should take action to amend or repeal legal acts found to be contrary to EU law.

According to Kolibiris, S. at the supranational level of the European Union legal order, the principle of primacy of European Union law holds a prominent position, as one of the general principles of European Union law, in relation to the Constitutional law of the Member States of the European Union.[21]

In Slovakia, the constitutional principle of primacy of EU law is applied, as the Constitution of the Slovak Republic (Act No. 460/1992 Coll.) in Article 7 (2) stipulates that: „*The Slovak Republic may, by an international treaty, ratified and promulgated in a manner laid down by law, or based on the treaty, transfer the exercise of a part of its powers to the European Communities and the European Union. Legally binding acts of the European Communities and the European Union shall have primacy over the laws of the Slovak Republic. The transposition of legally binding acts which require implementation shall be executed by law or a Government ordinance pursuant to Article 120 paragraph 2*".

Equally significant is the provision of article 1 paragraph 2 of the Constitution of the Slovak Republic, which includes that: „*Slovak Republic acknowledges and honours the general rules of international law, international treaties by which it is bound, and its other international obligations. "*

The Slovak Republic accepts, both by virtue of its Constitution and the courts' decisions, the primacy of EU law over national law. The given rule of recognition of this primacy relationship can also be seen as a characteristic feature of the legal system.

Slovak Law on Measures Related to the Governance of a Listed Company

Further to the above, the Slovak Republic adopted by the National Council of the Slovak Republic a law on certain measures related to the management of a listed company. The basic intention in the preparation of the draft law was the transposition of Directive (EU) 2022/2381 of the European Parliament and of the Council of 23 November 2022 on improving the gender balance among directors of listed companies and related measures. The objective of the legislation is gender equality in relation to corporate governance. This law applies to a listed company established in the territory of the Slovak Republic. A listed company is a company having its registered office in a Member State whose shares are admitted to trading on a regulated market in one or more Member States. Shares listed on a stock exchange usually mean more capital and greater prosperity for the company. The subjects of these relationships are listed companies carrying out business activities in the territory of the Slovak Republic, but the Directive does not apply to micro, small and medium-sized enterprises (SMEs) (with less than 250 employees). A listed company belongs to the category of joint stock companies which issues shares on financial markets admitted to

[21] Kolibiris, S. The Principle of Primacy of European Union law: a comparative approach in relation to the constitutional law of the Member States of the European Union. In Spanish Journal of Legislative Studies No. 4/2022. (2022). DOI: 10.21134/sjls.vi4.1783

trading. Listed companies are listed on a stock exchange whose shares are freely tradable, and investors can buy and sell shares. Listed companies are owned by many shareholders, while unlisted companies are owned by private investors. The decisions of listed companies are taken by a board of directors appointed by the shareholders.

Table 1: Comparison of Listed and Unlisted Company

	Listed company	**Unlisted company**
General characteristics	A listed company is a public company listed on a stock exchange whose shares are freely tradable.	An unlisted company is a company that is not listed on a stock exchange.
Ownership	Listed companies are owned by many shareholders. Listed shares represent the share capital of listed companies.	Unlisted companies are owned by private investors such as the founders, the founders' family and friends.
Liquidity of shares	The shares are highly liquid because there is a readily available market.	Shares do not have a readily available market; thus, they are illiquid.
Regulation	Stringent regulatory requirements.	Less stringent regulatory requirements.

Source: own processing

In the Table no 1. we compared the characteristics of listed and unlisted companies. Examples include company Lundbeck, which has been listed on the Copenhagen Stock Exchange since 1999 (Denmark) or Pepco, which has been listed on the Warsaw Stock Exchange (Poland) since May 2021.

In Slovakia there are two companies of this category, namely Tatra Banka, joint stock company and Tatry Mountain Resorts, joint stock company, which operates in the tourism sector. Both companies are listed on the Stock Exchange in Bratislava.

According to our assessment the Directive 2022/2381 applies to a smaller number of trading companies that are categorised as listed companies. The introduction of certain minimum requirements for listed companies without balanced gender representation relating to the selection of candidates for appointment or election to director positions on the basis of a transparent and clearly defined selection process and an objective comparative assessment of their qualifications in terms of suitability, competence and professional performance is necessary for achieving gender balance.[22] The increase in the representation of the under-represented gender in the Slovak Republic is represented by women.

The system that is to be introduced distinguishes between executive directors who are involved in the daily management of the company and non-executive directors who perform a supervisory function and are not

[22] Recital 24 Directive (EU) 2022/2381 of the European Parliament and of the Council of 23 November 2022 on Improving the Gender Balance among Directors of Listed Companies and Related Measures (Text with EEA relevance).OJ EU L 315, 7.12.2022, p. 44–59. Available at http://data.europa.eu/eli/dir/2022/2381/oj

involved in the daily management of the listed company. The management of a listed company relates to its top body - the statutory body or the supervisory body. It is the duty of a listed company to ensure that:

(a) representation of persons of the under-represented gender at least 40% in non-executive managers,
(b) to ensure a representation of the under-represented sex of at least 33 % in the executive managers,
(c) ensure that the under-represented sex is represented at a level of at least 33 % in management positions.

To illustrate it, the following table shows the total number of persons of the under-represented sex.

Table 2: Overview of the Number of Persons of the under-represented gender

Number of positions in the top management body of a listed company	Minimum number of non-executive directors performing supervisory functions. 40%	Minimum number of directors involved in the daily management of a listed company - members of the board of directors 33%
3	1 (33,3 %)	1 (33,3 %)
4	1 (25 %)	1 (25 %)
5	2 (40 %)	2 (40 %)
6	2 (33,3 %)	2 (33,3 %)
7	3 (42,9 %)	2 (28,6 %)
8	3 (37,5 %)	3 (37,5 %)
9	4 (44,4 %)	3 (33,3 %)

Source: (2024) Government of the SR. Draft of legal act on certain measures relating to the management of a listed company, available at: https://www.slov-lex.sk/legislativne-procesy/-/SK/LP/2024/175

A means of ensuring the application of the principle of equal opportunities for women and men and the achievement of gender balance (at the level of set quantitative targets) in the boards of listed companies is the establishment of a set of procedural requirements.
In selecting qualified candidates to improve gender balance in the boardroom, a listed company should consider a following factor:
(a) professional experience in managerial or supervisory tasks,
(b) international experience,
(c) multidisciplinarity,
(d) communication skills,
(e) networking abilities,
(f) knowledge in specific relevant areas such as finance, financial oversight or human resources management.

When selecting a candidate, the listed company must set out clear conditions for the selection process before the selection process itself, which also have to be clear, neutrally worded and unambiguous. Candidates for appointment or election to vacant directorships are to be selected based on an objective comparative assessment of the required qualifications. This concerns, in particular, the conditions laid down for filling vacant posts.

The selection of a candidate for the position of manager, which will be made in violation of the draft law, can be challenged in a court. Further to the above, the unsuccessful candidate of the under-represented sex is therefore granted *locus standi* to seek protection in court.

Listed companies will have the duty to inform the Ministry of Labour, Social Affairs and Family of the Slovak Republic about the gender balance of men and women in top management positions in companies in the form of regular reports. The current system of European Union law has a direct impact on the Slovak legal system and the legal systems in the Member States of the European Union, which shows that the process of European integration is constantly deepening and that obstacles to the proper functioning of the internal market are gradually being removed.

Examples from practice

The Slovak legal system has not yet included the specific legislation on the mandatory representation of men and women in management bodies. The representation of women in decision-making positions in Slovakia is quite heterogeneous, ranging from low representation of women (e.g. the Banking Council of the National Bank of Slovakia) to their predominant representation in, for example, the judiciary, education and even health care. Women are in a minority compared to men in most top positions of bodies of central state administration.

Table 3: Representation of Men and Women in Decision-making Positions

Company	Statutory body - Board of Directors Man/Woman	Supervisory Board Man/Woman	Sector
Tatrabanka, a.s.	5/2	5/2	Banking
Slovenská sporiteľna,a.s.	5/0	4/1	Banking
Nay, a.s.	2/0	1/ 2	Electronic retailer
Železiarne Podbrezova, a.s.	5/0	10/0	Steel production
Slovenská pošta, a.s.	2/3	3/4	Post services
Železnice SR, a.s.			Transport
Západoslovenská vodárenská spoločnosť, a.s.	6/1	17/ 2	Water supplier
Západoslovenská energetika, a.s.	5/0	6 / 2	Energy supplier
Národná diaľničná spoločnosť	5/0	3/2	Transport
Slovak Telekom, a.s.	1/2	2/3	Communication
Matador holding, a.s.	3/1	3/0	System supplier of automotive and non-automotive solutions
Slovnaft, a.s.	8/0	5/1	Chemical industry
Tatry Mountain Resorts, a.s.	1/2	8/1	Tourism

Source: own processing based on Business Register of the Slovak Republic on Internet - main page

To illustrate this, we have searched data in the Business Register of the Slovak Republic on the representation of women and men in the board of directors and the supervisory board (dual system of top management bodies) of some companies that have been operating on the market for a long time. We focused on companies with the legal form of a joint-stock company. Our findings are not positive. In most of the companies, only men are represented in the top management bodies. The most favourable situation is in both companies Slovenská pošta, a.s. (Slovak Post), joint stock company. However, as we can see, inequalities between women and men persist in many sectors of industry.

DISCUSSION

Equality between women and men in Slovakia is mainly guaranteed by the Constitution of the Slovak Republic, as well as by international conventions of international organisations to which the Slovak Republic has acceded and which are binding on it. Equality between women and men is a fundamental value on which the whole society thrives, while the elimination of stereotypes of women's representation in the top management bodies of commercial companies is not progressing. Achieving equal representation of women in decision-making and leadership positions is a topic that is currently discussed quite frequently. It was only with the adoption of Directive (EU) 2022/2381 that the participation of women in senior and managerial positions was made compulsory. The gender equality agenda as a cross-cutting priority should be part of all business entities. The level of gender equality is clearly linked to good governance, to ensuring full social participation based on individual qualities and abilities. In other words, it is about treating women and men fairly, considering their specific needs and life situations.

Men are dominant in entrepreneurial activity both in the European Union and in Slovakia. Despite the increasing participation of women in the labour market, their under-representation in overall entrepreneurial activity persists, possibly due to the work-life balance. In the long term, women have the highest share of entrepreneurs in the service sector and in the free professions. The free professions play an important role in social and economic development by providing jobs, contributing to economic growth and fulfilling important social security functions. Lack of managerial experience is also one of the barriers to women starting a business. Access to finance and capital is also an obstacle to women's entrepreneurial activity. Despite the problems identified, many women do not lack the skills but the confidence and courage to start business on their own. Economically active women are most active in the Bratislava region of Slovakia.

CONCLUSION

Measures taken by the European Union on gender equality contribute to the objectives and values of the European Union. The Union´s system of gender representation in company boards facilitates women's participation in the decision-making of listed companies. In this article, we have identified, through a systemic analysis, the legal provisions establishing equal status for men and women, as well as the protection of social rights. At the same time, we have explained the transposition of the Directive into the Slovak legal order and clarified the conditions concerning gender representation in the top management bodies, regarding the representation of women in these bodies. The forthcoming Slovak law on measures related to the governance of listed companies will have positive effects on the business environment and a positive social impact.

At the same time, we have also highlighted the current state of gender representation in some selected companies that have been on the market for a long time. Based on the facts, we have concluded that the European Union is improving the position of women in the labour market through a system of coordination. Although the scientific study offers a conceptual normative framework regarding gender-balanced representation at all levels of management, the question of social responsibility in the integration of disadvantaged groups of people with disabilities as well as inclusive and diverse leadership remains open.

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