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Women's Participation in ICT and Regional Development: A Two-Way Fixed Effects Approach

Peter Karácsony[a], Gulbakhyt Olzhebayeva[b]*

[a]Obuda University, Budapest, Hungary
[b]Almaty Management University, Almaty, Kazakhstan

ABSTRACT

Women's participation in the information and communication technology (hereinafter - ICT) sector It is increasingly seen as an essential element of inclusive digital transformation. This study examines the impact of digitalization and gender-related indicators on regional economic growth and evaluates whether women's participation in ICT contributes to more inclusive development patterns. The analysis is based on a balanced panel dataset of 16 regions for the period 2010–2024. A pooled OLS model, a two-way fixed effects specification, and robustness checks with clustered heteroskedasticity-robust standard errors are employed. Estimates of the two-factor model of fixed effects show that the wage level is the most stable determinant of regional economic growth ($\beta = 1.330$; $p < 0.001$), while investments in fixed assets retain marginal statistical significance ($\beta = 0.126$; $p = 0.060$). The human capital index shows a statistically significant negative internal effect ($p < 0.001$), while indicators of digitalization and gender variables turn out to be statistically insignificant. The results show that digitalization indicators and gender variables do not have a statistically significant intraregional impact on the gross regional product after taking into account regional and temporary fixed effects. At the same time, investments in fixed assets and wages are the most stable determinants of regional growth. Cluster analysis revealed four models of regional development — digital-service, industrial, agricultural and resource, which confirms the structural heterogeneity. The results show that digitalization by itself does not guarantee inclusive growth, and its economic effects are mediated by structural factors.

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***Corresponding author:** Olzhebayeva G. – PhD candidate, Almaty Management University, Almaty, Kazakhstan, email: g.olzhebayeva@gmail.com

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Әйелдердің АКТ саласына қатысуы және өңірлік даму: тұрақты әсерлердің екі факторлы моделі

Карачони П.[а]*, Олжебаева Г.[б]*

[а]Обуда Университеті, Будапешт, Венгрия
[б]Алматы Менеджмент Университеті, Алматы, Қазақстан

ТҮЙІН

Әйелдердің ақпараттық-коммуникациялық технологиялар (бұдан әрі – АКТ) секторына қатысуы инклюзивті цифрлық трансформацияның маңызды элементі ретінде жиі қарастырылуда. Зерттеуде цифрландыру және гендерлік көрсеткіштердің өңірлік экономикалық өсуге ықпалы талданып, АКТ саласындағы әйелдердің қатысуы неғұрлым инклюзивті даму үлгілерінің қалыптасуына ықпал ете ме деген мәселе бағаланады. Талдау 2010–2024 жж. аралығындағы Қазақстанның 16 өңірі бойынша теңгерілген панельдік деректерге негізделген. Pooled OLS моделі, екі факторлы тұрақты әсерлер (Two-way Fixed Effects) моделі және гетероскедастикалыққа орнықты, кластерленген стандартты қателер қолданылды. Екі факторлы тұрақты әсерлер моделінің бағалаулары жалақы деңгейінің өңірлік экономикалық өсудің ең тұрақты детерминанты екенін көрсетеді ($\beta = 1.330$; $p < 0.001$), ал негізгі капиталға инвестициялар шекті статистикалық мәнділікті сақтайды ($\beta = 0.126$; $p = 0.060$). Адам капиталы көрсеткіші статистикалық тұрғыдан мәнді теріс ішкіөңірлік әсерді көрсетеді ($p < 0.001$), ал цифрландыру индикаторлары мен гендерлік айнымалылар статистикалық тұрғыдан мәнді емес болып табылады.Нәтижелер цифрландыру көрсеткіштері мен гендерлік айнымалылардың өңірлік және уақыттық тұрақты әсерлерді ескергеннен кейін жалпы өңірлік өнімге статистикалық мәнді ішкіөңірлік ықпал етпейтінін көрсетеді. Сонымен қатар, негізгі капиталға инвестициялар мен жалақы деңгейі өңірлік өсудің ең тұрақты детерминанттары ретінде айқындалады. Кластерлік талдау өңірлік дамудың төрт моделін — цифрлық-қызмет көрсету, индустриялық, аграрлық және ресурстық — анықтап, құрылымдық гетерогендікті растайды. Алынған нәтижелер цифрландырудың өзі инклюзивті өсуді автоматты түрде қамтамасыз етпейтінін, ал оның экономикалық әсерлері құрылымдық факторлар арқылы жүзеге асатынын көрсетеді.

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***Хат-хабаршы авторы:** Олжебаева Г.– PhD докторанты, Алматы Менеджмент Университеті, Алматы, Қазақстан, email: g.olzhebayeva@gmail.com

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Участие женщин в ИКТ и региональное развитие: двухфакторная модель фиксированных эффектов

Карачони П.[а]*, Олжебаева Г.[б]*

[а]Университет Обуда, Будапешт, Венгрия
[б]Алматинский университет менеджмента, Алматы, Казахстан

АННОТАЦИЯ

Участие женщин в секторе информационно-коммуникационных технологий (далее – ИКТ) все чаще рассматривается как важнейший элемент инклюзивной цифровой трансформации. В исследовании анализируется влияние цифровизации и гендерных показателей на региональный экономический рост, а также оценивается, способствует ли участие женщин в ИКТ формированию более инклюзивных моделей развития. Эмпирический анализ основан на сбалансированной панельной выборке из 16 регионов Казахстана за период 2010–2024 гг. Использованы объединенная модель (Pooled OLS), двухфакторная модель фиксированных эффектов (Two-way Fixed Effects), а также проверки устойчивости с применением кластеризованных робастных стандартных ошибок. Оценки двухфакторной модели фиксированных эффектов показывают, что уровень заработной платы является наиболее устойчивым детерминантом регионального экономического роста ($\beta = 1.330$; $p < 0.001$), тогда как инвестиции в основной капитал сохраняют предельную статистическую значимость ($\beta = 0.126$; $p = 0.060$). Показатель человеческого капитала демонстрирует статистически значимый отрицательный внут-региональный эффект ($p < 0.001$), в то время как индикаторы цифровизации и гендерные переменные оказываются статистически незначимыми. Результаты показывают, что показатели цифровизации и гендерные переменные не оказывают статистически значимого внутрегионального влияния на валовой региональный продукт после учета региональных и временных фиксированных эффектов. В то же время инвестиции в основной капитал и уровень заработной платы выступают наиболее устойчивыми детерминантами регионального роста. Кластерный анализ выявил четыре модели регионального развития — цифрово-сервисную, индустриальную, аграрную и ресурсную, что подтверждает структурную гетерогенность. Полученные результаты свидетельствуют о том, что цифровизация сама по себе не гарантирует инклюзивного роста, а ее экономические эффекты опосредуются структурными факторами.

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***Автор-корреспондент:** Олжебаева Г.– PhD докторанты, Алматинский университет менеджмента, Алматы, Казахстан, email: g.olzhebayeva@gmail.com

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1. Introduction

Digital transformation leads to social shifts affecting the nature of employment, income distribution, and opportunities for economic integration across various groups of the population (Chen et al., 2020; Pedchenko et al., 2021; Berardi & Valentinetti, 2022). Women's participation in the information and communication technology (hereinafter – ICT) sector is an indicator of social inclusion and gender equality in the digital economy (Yin et al., 2023). Despite rising levels of women's education and greater access to higher education, gender differences in pay, occupational segregation, and access to high-paying technology professions persist (Cruz et al., 2025). The development of ICT creates new opportunities for professional mobility, flexible employment, and income growth, but the extent to which these opportunities are used varies significantly between regions (Mumporeze & Prieler, 2017; Amber & Chichaibelu, 2023; Nguyen et al., 2025). Kazakhstan's regional heterogeneity in terms of urbanization, industry specialization, investment activity, and digital infrastructure development creates a different social and economic opportunites for women's involvement in the digital economy.

In the context of the implementation of government programs for digitalization and modernization of the economy, the issue of ICT contribution to the reduction of gender disparities and the formation of more inclusive regional labor markets is relevant. Economic growth does not automatically ensure a reduction in social inequality, while digitalization may both expand opportunities and reinforce existing structural barriers.

Existing studies primarily consider digitalization as a factor of economic growth, paying insufficient attention to its social consequences and the gender dimension of regional development. The lack of panel studies that account for interregional heterogeneity and time dynamics is particularly noticeable in Kazakhstan.

The research aims to identify the impact of women's participation in the ICT sector on the processes of social and economic transformation of Kazakhstan's regions, as well as to assess whether digitalization contributes to the formation of more inclusive and gender-balanced regional labor markets.

To achieve this goal, the following hypotheses have been formulated:

H1: Digitalisation of the region has a positive impact on economic growth.

H2: Gender indicators (gender wage gap, percentage of women in ICT, female unemployment rate) do not have a stable within-region impact on economic growth after taking into account fixed effects.

H3: Human capital (graduates per 10,000 population) is a significant factor in regional dynamics, but its impact may vary in the short term and in the interregional perspective.

H4: Investment in fixed capital and wage levels are key determinants of within-region economic growth.

H5: Regional differences in employment structure and digitalization form stable regional types (clusters) with distinct profiles of wages, sectoral composition, and gender indicators.

The empirical analysis is based on a balanced panel of 16 regions in Kazakhstan for the period 2010-2024 and uses a two-factor fixed-effects model, which allows distinguishing between inter-regional structural differences and intra-regional dynamics. Additional cluster analysis provides a typological interpretation of the identified dependencies.

2. Literature review

Digitalization considered as a structural factor in the transformation of social and economic relations, but its impact on gender equality remains ambiguous. The development of ICT expands women's economic opportunities by strengthening their participation in the labor market and entrepreneurship (Mariscal et al., 2019). At the macro level, a higher level of digital development is associated with a decrease in gender and income inequality, and in countries with high digital maturity, a decrease in gender gaps is recorded (Thanh et al., 2022; Shah & Krishnan, 2024; Tunçsiper, 2025).

At the same time, digitalization does not eliminate structural forms of inequality automatically. The gender digital divide is interpreted as a multi-level phenomenon involving differences in skills, the intensity of technology use, and the ability to extract economic benefits from digital resources (Ogbo et al., 2021; Pham et al., 2025). Even with the narrowing of the access gap, differences between the second and third levels persist, especially in less developed areas, indicating a limited infrastructural approach (Zhao & Kuang, 2025).

Digital inequality has a significant territorial dimension. The level of digital integration is systematically higher in economically developed and urbanized regions, while the gender gap is widening in peripheral territories (Ay & Kılıç, 2023). The quality of regional institutions further modifies the scale of the digital divide (Caragliu & Del Bo, 2025). Empirical studies show that the impact of digitalisation on wages and gender wage gaps varies significantly across urban and rural regions, and women's digital access is closely linked to infrastructure, education, and social norms (Mumporeze & Prieler, 2017; Amber & Chichaibelu, 2023; Nguyen et al., 2025). Consequently, the effects of digital transformation are mediated by regional development levels.

Digital competencies are the central mechanism through which digitalization affects gender equality. Increasing qualification requirements increases competition in the labor market and, with uneven access to education, reproduces professional differences (Beregovskaya et al., 2022). Gender differences in digital training persist even with infrastructure expansion, while targeted educational interventions demonstrate the potential to narrow the gap in STEM fields (Sanchez-Canut et al., 2023; Freire et al., 2026).

The impact of digitalization on the employment structure remains controversial. Even in institutionally developed economies, horizontal and vertical segregation in the ICT sector persists, and the organizational practices of digital companies reproduce gender hierarchies (Proctor-Thomson, 2013; Holth et al., 2017). Automation transforms, but does not eliminate, forms of inequality (Persson & Wallo, 2024). At the same time, some studies have documented the potential of digital transformation to overcome the “glass ceiling” and expand women's managerial opportunities, indicating that the effects depend on the institutional and industry contexts (Tian et al., 2025; Pereira, 2014).

The gender pay gap remains stable. Empirical estimates reveal a significant unexplained component of the wage gap, the persistence of differences in STEM sectors, and the impact of ownership structure on the scale of the gap (Kritikos et al., 2024; Cruz et al., 2025). At the same time, higher levels of education and digitalisation are associated with a decrease in gender wage differentiation, and the development of ICT at the macro level correlates with a reduction in gender and income inequality (Lukyanova, 2021; Shah & Krishnan, 2024). Thus, digitalization functions as a factor that can either mitigate or reproduce gender disparities, depending on institutional and territorial conditions.

Methodologically, the analysis of these relationships is primarily based on panel models that allow consideration of temporal dynamics and unobserved heterogeneity. At the cross-country level, fixed-effects models are used to assess the impact of ICT on gender and income indicators (Kabanov et al., 2024; Islam & Akhtar, 2026). At the subnational level, regional panels reveal the heterogeneity of the impact of digitalization on wages and gender parameters, while spatial studies emphasize the institutional determinants of the digital divide (Lukyanova, 2021; Nguyen et al., 2025; Caragliu & Del Bo, 2025).

For Kazakhstan, existing studies demonstrate either the potential of digital platforms to expand women's economic activity or the territorial differentiation of educational infrastructure. Still, they do not offer an integrated econometric assessment of the structural channels of digitalization's impact on gender inequality in the context of regional asymmetry (Kireyeva et al., 2022a; Kireyeva et al., 2022b). In this regard, the study relies on the framework of structurally embedded digital transformation, integrating a general-purpose technology approach and the concept of a multi-level digital divide to explain the territorial and gender heterogeneity of the economic effects of digitalization.

Despite a significant increase in the number of studies examining the relationship between digitalisation and gender equality, the existing literature remains fragmented by levels of analysis and methodological approaches. Most of the work focuses either on cross-country comparisons that capture the aggregate macro effects of ICT on indicators of gender and income inequality, or on individual aspects of the digital divide without integrating them into a single analytical framework. As a result, there remains a methodological gap among digital infrastructure research, work on the gender segregation of the labour market, and regional development models. The in-country panel effects of digitalisation have not been sufficiently studied, while accounting for gender, educational, institutional, and territorial factors, which limits the ability to identify the structural mechanisms through which digital transformation transforms or reproduces inequality.

3. Research methods

The research based on quantitative analysis of region panel data of Kazakhstan for the period 2010-2024. The balanced panel (16 regions, N=240) allow controlling both temporal dynamics and cross-regional heterogeneity. The analysis include corelation, regression, clustering. The choice of panel data is methodologically justified by a number of reasons. First of all, the panel format allows us to simultaneously account for both interregional differences and the temporal dynamics of indicators, which is especially important when analysing gender imbalances and the transformation of regional labour markets, where both stable structural factors and changes over time shape the results. In addition, panel models allow control for unobservable heterogeneity across regions. Features such as the institutional environment, industry specialization, demographic structure, or social and cultural characteristics are often relatively stable and difficult to directly measure. Using models with fixed or random effects allows us to identify the net effect of explanatory variables, accounting for these latent factors. Panel data also increases the number of observations and degrees of freedom, thereby improving the statistical effectiveness of estimates and reducing the risk of multicollinearity compared to purely cross-sectional or time-based analyses.

Finally, the panel approach enables identification of intra-regional changes over time, which is crucial for assessing the impact of digitalisation, structural shifts in employment, and social infrastructure development on the gender pay gap and women's participation in the ICT sector. Together, this forms a more stable and analytically grounded empirical basis for the study of factors in gender inequality and the structural transformation of the regional economy. Data retrieved from the National Bureau of Statistics for the period 2010-2024. Regional indicators of labour market, structure of employment, digitalization, and economic development are used. The analysis incorporates regional indicators reflecting labour market conditions, employment structure, digitalization, and economic development.

Table 1 presents the description and classification of the variables used in the empirical model.

Table 1. Descriptive statistics of variables.

Section	Variable	Code	Mean	SE	SD	Min	Max
Regional Economic Development	Gross regional product	*grp*	12403,82	587,95	9108,47	2150,30	48109,40
	Investment in fixed capital per capita	*inv_pc*	0,72	0,06	0,88	0,09	6,83
	Urbanization Rate	*urban*	56,70	1,48	23,00	12,99	100,00
	Average Monthly Wage	*wage*	184390,22	7388,78	114466,52	51340,00	633322,00
	Gender Wage Gap	*gwg*	26,14	0,81	12,61	-0,18	58,90
Labor Market Structure and Sectoral Employment	Share of Women Employed in ICT	*wic_it*	43,49	0,58	8,91	16,17	75,38
	Total ICT Employment	*ict_it*	1,64	0,07	1,16	0,26	6,35
	Share of Employment in Service	*serv_emp*	61,50	0,67	10,31	37,28	85,36
	Share of Employment in Agriculture	*agr_emp*	17,38	0,86	13,35	0,18	53,12
	Share of Employment in Industry	*ind_emp*	21,13	0,48	7,45	7,86	42,62
	Female Unemployment Rate	*funemp*	5,63	0,06	0,88	3,90	9,70
Human Capital and Digital Development	Graduates per 10K population	*grad_emp*	14838,15	733,84	11368,55	1301,16	73790,81
	Share of Internet Users	*internet_it*	75,66	1,16	18,01	21,60	98,65
Social Infrastructure and Early Childhood Support	Childcare Coverage (0–3 years)	*childcare03*	36,57	1,51	23,42	0,68	95,61
	Preschool Enrollment Rate	*preschool*	48,69	0,74	11,51	14,80	77,70

Note: compiled by the authors.

The variables are grouped into four analytical blocks: regional economic development, employment structure and labor market, human capital and digital development, as well as social infrastructure. The mean values, standard errors, standard deviations and the range of variation of

indicators for the period 2010-2024 for 16 regions of Kazakhstan are given. The data obtained indicate a high interregional differentiation in GRP, wages, and investment activity, reflecting the heterogeneity in the economic development of the territories. Significant variability is also observed in the gender wage gap (from negative values to 58.9%), as well as in the structure of employment, especially in agriculture and the service sector. Indicators of digitalization, human capital, and preschool education coverage for children under three show significant variation, which confirms differences in the level of technological development and educational potential of regions.

The revealed variability in indicators necessitates a comprehensive analysis of the interrelationships among economic, structural, and social factors. The logic of empirical research and the sequence of analytical steps are shown in Figure 1.

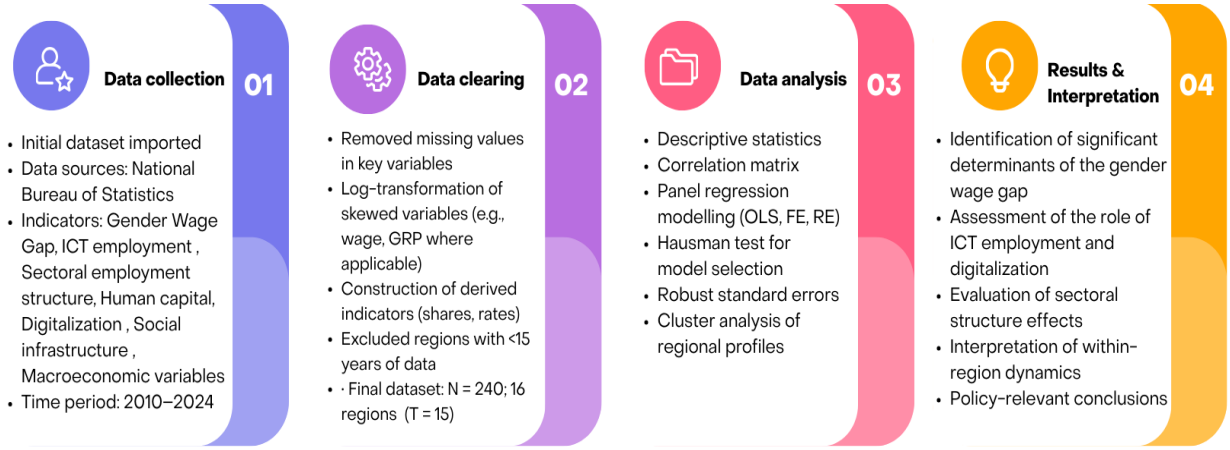

Figure 1. The stages of research.

The conceptual and methodological logic of the conducted research is structured as a sequence of stages. In the first stage, a database is being compiled from regional statistical indicators for 2010-2024. The second stage includes preliminary processing of information: checking the completeness of observations, transforming variables, and constructing derived indicators. The third stage is represented by a set of statistical and econometric procedures, including the calculation of descriptive statistics, correlation analysis, evaluation of panel regression models and diagnostic tests, and clustering of regions by structural characteristics. The final stage aims to interpret the results and identify the significant factors that determine the gender wage gap and the specifics of regional structural transformation.

First, the Pearson correlation matrix was calculated, enabling estimation of linear relationships among the model variables. The correlation matrix is a preliminary diagnostic analysis aimed at identifying multicollinearity that can distort regression parameter estimates.

Next, a regression analysis of the panel data was performed. The basic specification of the empirical model is as follows (1):

$$\ln(GRP_{it}) = \beta_1 gwg_{it} + \beta_2 wic_{it} + \beta_3 ict_{it} + \beta_4 agr_{it} + \beta_5 ind_{it} + \beta_6 grad_{it} + \beta_7 internet_{it} + \beta_8 funemp_{it} + \beta_9 \ln(wage_{it}) + \beta_{10} childcare_{it} + \beta_{11} preschool_{it} + \beta_{12} urban_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where α_i – unmeasurable regional effects;
γ_t – temporary effects;
ε_{it} – a random error.

At the first stage, a Pooled OLS model was evaluated, assuming regional uniformity and the absence of individual effects. Next, models with fixed Effects (FE) and random Effects (RE) were constructed to allow for unobserved regional heterogeneity. The fixed effects model controls for time-invariant region-level features by transforming the data, whereas the random effects model assumes the random nature of individual differences and their uncorrelation with explanatory variables.

The choice between the FE and RE models was based on the Haussmann test. The obtained statistical value was 115,03 in the squared form, with $p < 0,001$, indicating rejection of the null hypothesis of the validity of the estimates in the random effects model. Thus, the assumption of uncorrelated individual effects with the regressors is not confirmed.

Consequently, in the further analysis, a Two-way Fixed Effects model is used, which takes into account both regional α_i and temporal γ_t effects, which ensures the consistency and interpretative correctness of the estimates obtained. Robust standard errors (HC1), resistant to heteroscedasticity and autocorrelation, were used to increase the reliability of the results. Additionally, an analysis of the residuals was carried out to verify the model's functional form and the absence of systematic deviations.

Next, a cluster analysis of regions was conducted to identify groups of regions with similar employment patterns, levels of digital development, and social and economic characteristics. Clustering enabled the supplementation of regression results with a typological interpretation, revealing stable models of regional development and differences in the trajectories of structural transformation.

The study has a number of limitations. Firstly, the analysis is based on aggregated regional data, which does not allow for consideration of the individual characteristics of employees and the micro-level mechanisms of gender gap formation. Secondly, indicators of digitalization and employment in ICT reflect quantitative, but not qualitative, employment parameters. Thirdly, despite the use of a two-factor fixed-effects model, it is impossible to completely eliminate endogeneity, which limits the interpretation of cause-and-effect relationships. Finally, possible changes in statistical methodology and the impact of external macroeconomic shocks during the period under review may further affect the dynamics of indicators.

4. Results

An analysis of the current state of women's employment in the information and communication technology sector enables assessment of the degree of female involvement in ICT. The ICT sector plays a crucial role in shaping the digital economy, increasing labor productivity and structural modernization of regions, which makes the gender aspect of employment in this area particularly significant.

There was a steady growth of digitalization, accompanied by an expansion of employment in ICT in the period 2010-2024. At the same time, women's participation in ICT sector is characterized by significant inter-regional differentiation and heterogeneity over time. This indicates the presence of structural factors affecting women's access to high-tech economic activities.

For a more detailed assessment of the interregional dynamics of women's participation in the information and communication technology sector, a graphical analysis of the indicator of the proportion of women in ICT by region for the period 2010-2024 is presented. Figure 2 illustrates the trajectories of changes of the Women in ICT (wic_it) indicator for each region, allowing us to identify both stable trends and fluctuations over time.

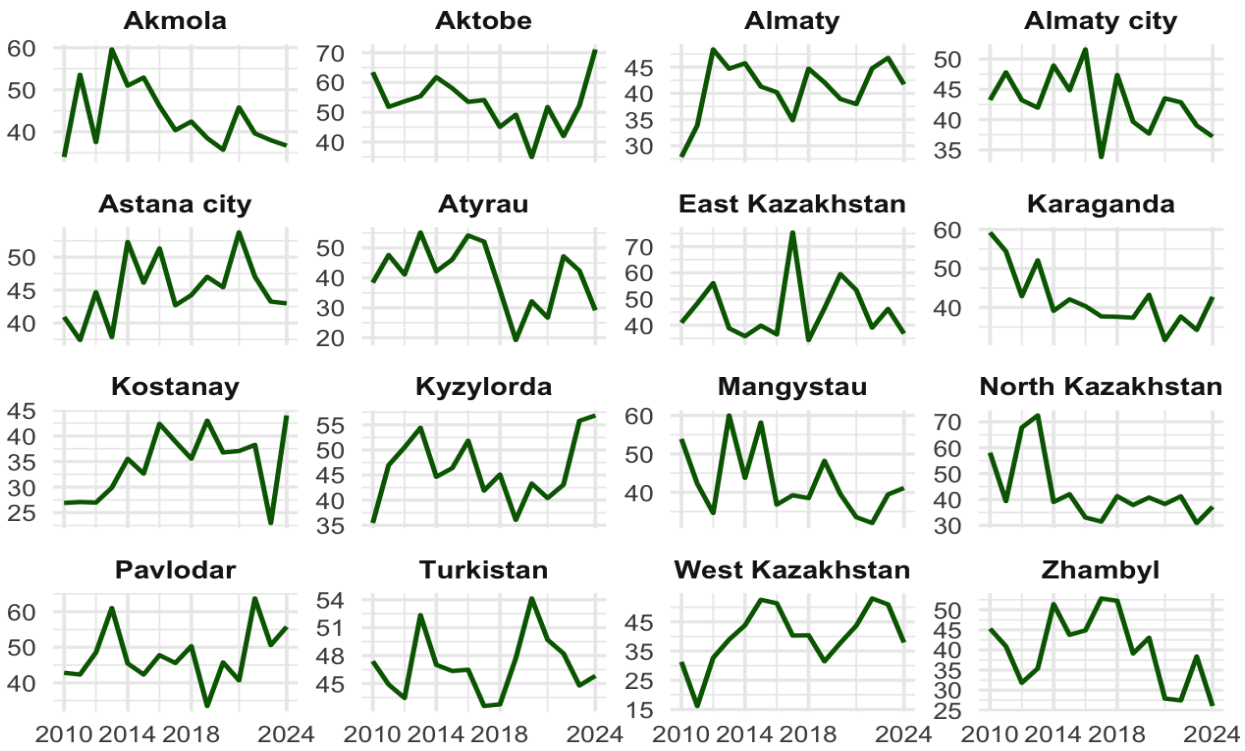

Figure 1. Regional changes in women's participation in the ICT sector in Kazakhstan for 2010-2024.

The analysis demonstrates a pronounced regional heterogeneity of women's participation in ICT. In a number of regions (for example, Aktobe, North Kazakhstan region, East Kazakhstan region), there have been periods of significant growth in the indicator with subsequent fluctuations, which may indicate a structural restructuring of the labor market or a change in industry specialization. In the largest cities, Almaty and Astana, the dynamics is characterized by relative stability with moderate fluctuations, reflecting a more diversified and institutionally stable economic environment.

The Kyzylorda and Zhambyl regions have a changing path, which may be due to the limited capacity of the high-tech sector and dependence on individual investment projects. Individual peaks in the dynamics of a number of regions indicate the influence of temporary factors, including government digitalization programs and external macroeconomic shocks. In general, the graphical analysis confirms the presence of significant interregional differences and temporal variability in

women's participation in ICT, which justifies the use of panel regression models to identify the factors that determine these differences.

To assess the structure of relationships among the studied variables and identify possible multicollinearity issues, a correlation matrix has been constructed. Figure 3 shows the coefficients of paired correlation between the main economic, structural, digital and social indicators included in the model.

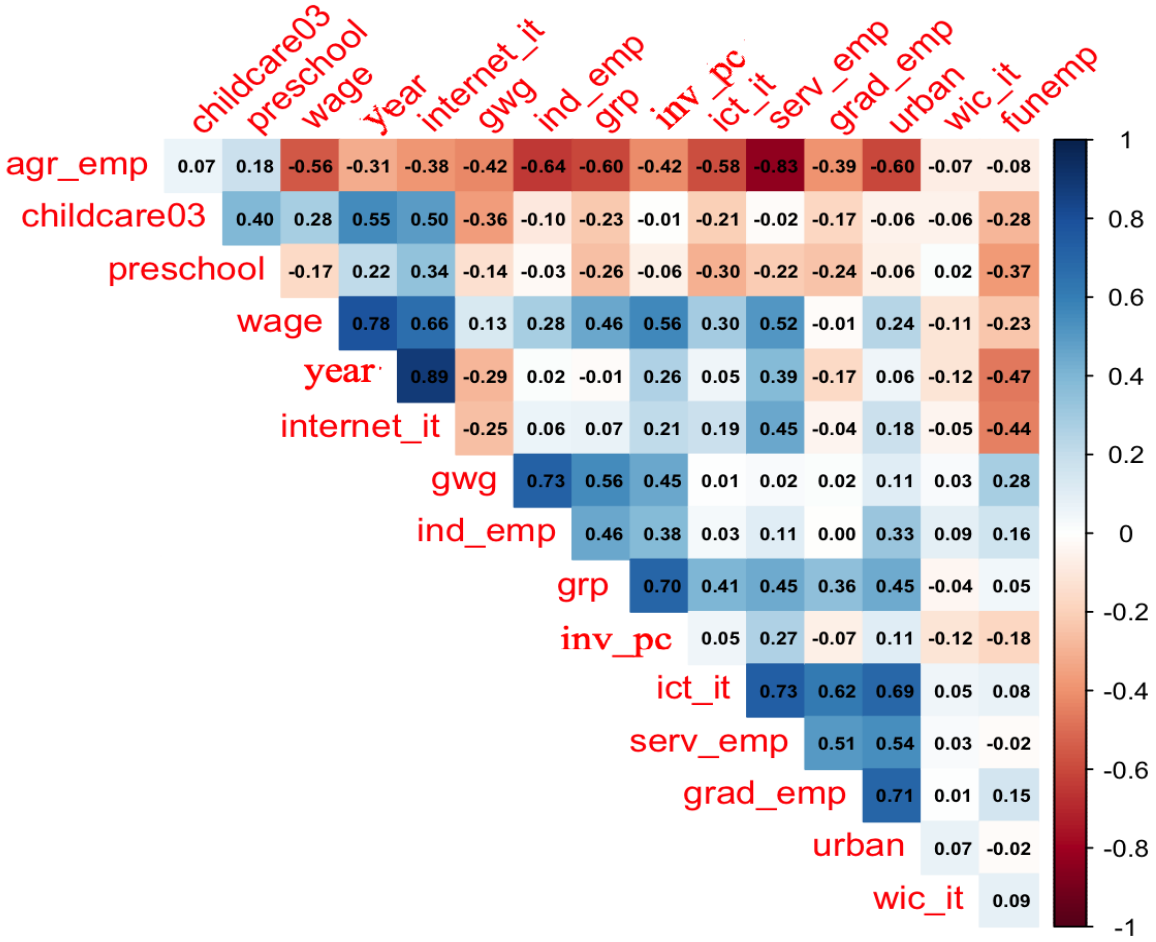

Figure 3. Correlation matrix.

The correlation matrix reveals several stable, economically interpretable relationships among the model variables. Indicators of economic development demonstrate pronounced positive associations. Gross regional product (grp) is strongly correlated with the gender wage gap (gwg: r = 0.70), industrial employment (ind_emp: r = 0.56), ICT employment (ict_it: r = 0.45), and the share of graduates (grad_emp: r = 0.45). Average monthly wages are correlated with the time trend (year: r = 0.78) and the level of internet penetration (internet_it: r = 0.66), reflecting the overall growth of incomes and digitalization over the period under consideration.

Regional structural differentiation is manifested in negative relationships between agricultural employment and indicators of technological and service-sector development. The

share of employment in agriculture (agr_emp) is negatively correlated with ICT employment (ict_it: r = –0.58), the share of graduates (grad_emp: r = –0.60), gross regional product (grp: r = –0.60), and particularly with the share of employment in services (serv_emp: r = –0.83). This configuration reflects the contrast between agrarian and service-digital models of regional economic development. Indicators of digital transformation form an interconnected group. ICT employment (ict_it) is positively associated with the share of graduates (grad_emp: r = 0.69), employment in the service sector (serv_emp: r = 0.62), and internet penetration (internet_it: r = 0.45). The share of graduates correlates strongly with the gender wage gap (gwg: r = 0.73), suggesting greater income differentiation in more developed educational centres.

The relationship between the gender wage gap and the share of women in ICT (wic_it: r = 0.03) is neutral, suggesting no simple linear dependence at the aggregate level. Female unemployment is negatively correlated with internet penetration (funemp and internet_it: r = –0.44) and with the time trend (year: r = –0.47), indicating a gradual decline in female unemployment over time. The correlation coefficients do not exceed critical thresholds (|r| > 0.9), indicating the absence of severe multicollinearity and supporting the inclusion of these variables in the panel regression model.

The structural variable representing the share of employment in the service sector (serv_emp) was excluded from the subsequent regression analysis. This decision was обусловлено высокой корреляцией with alternative indicators of sectoral employment structure and the presence of a linear dependency among sectoral employment shares, the sum of which approaches unity. Retaining this variable would lead to perfect multicollinearity and, consequently, prevent consistent estimation of the model parameters.

In the first stage of the empirical analysis, Pooling OLS was evaluated without accounting for individual regional and temporal effects. This specification assumes the uniformity of observations and serves as a reference point for subsequent comparison with fixed- and random-effects models. The estimation was performed using the least-squares method with classical standard errors. Table 2 presents estimates of pooling model coefficients (Pooling OLS) with classical standard errors.

Table 2. Results of Pooling OLS with classical standard errors.

Variable	Estimate	Std_Error	t_value	p_value	Sig
(Intercept)	5,706	1,138	5,014	0,000	***
gwg	0,013	0,003	4,671	0,000	***
wic_it	-0,001	0,002	-0,346	0,729	
ict_it	0,048	0,031	1,567	0,118	
agr_emp	0,013	0,003	3,730	0,000	***
ind_emp	0,008	0,006	1,383	0,168	
grad_emp	0,000	0,000	6,187	0,000	***
internet_it	-0,004	0,002	-1,792	0,074	.
funemp	0,033	0,026	1,299	0,195	
ln_wage	0,205	0,095	2,165	0,031	*
childcare03	-0,002	0,001	-2,026	0,044	*
preschool	0,002	0,002	0,866	0,387	
ln_inv_pc	0,471	0,050	9,401	0,000	***
urban	0,008	0,002	4,718	0,000	***

Note: compiled by the authors.

The analysis of the results indicates that the gender wage gap (gwg) is positively and statistically significantly associated with the level of economic development (β = 0.0131; p < 0.01).

Investment in fixed capital per capita (ln_inv_pc: $\beta = 0.471$; $p < 0.01$), the share of graduates (grad_emp: $\beta \approx 0.000$; $p < 0.01$), the level of urbanization (urban: $\beta = 0.008$; $p < 0.01$), and the share of employment in agriculture (agr_emp: $\beta = 0.013$; $p < 0.01$) also demonstrate positive and highly significant effects.

The logarithm of average monthly wages (ln_wage) exerts a positive influence ($\beta = 0.205$; $p < 0.05$), which is consistent with theoretical expectations. The variable capturing childcare coverage for children under three years of age (childcare03) exhibits a statistically significant negative coefficient ($\beta = -0.002$; $p < 0.05$), potentially reflecting structural characteristics of regions with more developed social infrastructure.

ICT employment (ict_it), the share of women in ICT (wic_it), industrial employment (ind_emp), female unemployment (funemp), and preschool enrollment (preschool) are not statistically significant within this specification. The share of Internet users (internet_it) shows a negative effect at the 10% significance level ($\beta = -0.004$; $p \approx 0.07$). These findings are preliminary, as the pooled OLS model does not account for regional heterogeneity. Subsequent sections compare the results with fixed-effects and random-effects specifications.

The coefficient of determination ($R^2 = 0.836$) indicates that the model explains approximately 83.6% of the variation in the logarithm of gross regional product. The adjusted R^2 (0.826) remains high, suggesting the robustness of the estimates given the number of included regressors. The F-statistic ($F = 88.41$, $df1 = 13$, $df2 = 226$) is statistically significant at $p < 2.22 \times 10^{-16}$, confirming the joint significance of the explanatory variables.

At the same time, the high explanatory power of the pooled model does not preclude potential bias arising from the omission of regional and time effects. Therefore, the subsequent analysis compares the results from fixed-effects and random-effects models. To assess the robustness of the estimates, the pooled model was additionally re-estimated using heteroskedasticity-robust standard errors of the HC1 type.

Table 3 presents the results from the pooled OLS model with HC1-robust standard errors.

Table 3. Results of the pooled panel model (Pooling OLS) with robust standard errors (HC1).

Variable	Estimate	Std_Error_HC1	t_value	p_value	Sig
(Intercept)	5,706	1,355	4,212	0,000	***
gwg	0,013	0,005	2,514	0,013	*
wic_it	-0,001	0,003	-0,231	0,818	
ict_it	0,048	0,051	0,948	0,344	
agr_emp	0,013	0,005	2,807	0,005	**
ind_emp	0,008	0,009	0,845	0,399	
grad_emp	0,000	0,000	5,186	0,000	***
internet_it	-0,004	0,003	-1,337	0,183	
funemp	0,033	0,024	1,367	0,173	
ln_wage	0,205	0,113	1,821	0,070	.
childcare03	-0,002	0,002	-1,385	0,167	
preschool	0,002	0,004	0,521	0,603	
ln_inv_pc	0,471	0,069	6,798	0,000	***
urban	0,008	0,003	2,353	0,020	*

Note: compiled by the authors.

The application of heteroskedasticity-robust (HC1) standard errors increases the estimated standard errors for several variables and, consequently, reduces the statistical significance of

certain coefficients. Nevertheless, the key determinants retain both their significance and direction of effect.

Investment in fixed capital per capita (ln_inv_pc) remains the strongest and most statistically significant determinant of economic development ($\beta = 0.471$; $p < 0.001$). The human capital indicator – the share of graduates (grad_emp: $\beta \approx 0.000$; $p < 0.001$) – also preserves a substantial positive effect. The gender wage gap (gwg) continues to be positively associated with the level of GRP ($\beta = 0.013$) and remains statistically significant at the 5% level ($p = 0.013$), although its significance decreases relative to estimates obtained with classical standard errors. The share of employment in agriculture (agr_emp) also remains significant ($\beta = 0.013$; $p < 0.01$). The level of urbanization (urban) preserves a positive and statistically significant effect ($\beta = 0.008$; $p < 0.05$). At the same time, variables related to digitalization (wic_it, ict_it, internet_it) do not demonstrate statistical significance within the pooled model with robust standard errors. The variable ln_wage retains marginal significance at the 10% level ($p \approx 0.07$). Indicators of social infrastructure (childcare03, preschool) lose statistical significance after correcting for heteroskedasticity.

These findings indicate the relative robustness of the core economic determinants, while also confirming the necessity of transitioning to models that account for regional heterogeneity, as the pooled specification does not control for individual regional effects.

In light of the Hausman test results, further analysis is conducted using a two-way fixed effects model that accounts for both regional and time-specific heterogeneity. This specification allows control for time-invariant regional characteristics as well as common macroeconomic shocks and trends affecting all regions simultaneously. Estimation is performed using classical standard errors. Table 4 presents the estimation results for the two-way fixed-effects model.

Table 4. Two-way Fixed Effects.

Variable	Estimate	Std_Error	t_value	p_value	Sig
gwg	-0,004	0,003	-1,435	0,153	
wic_it	0,000	0,001	0,191	0,849	
ict_it	-0,011	0,021	-0,517	0,606	
agr_emp	-0,004	0,003	-1,419	0,157	
ind_emp	0,016	0,005	3,043	0,003	**
grad_emp	0,000	0,000	-4,176	0,000	***
internet_it	0,001	0,001	0,926	0,356	
funemp	-0,013	0,011	-1,100	0,273	
ln_wage	1,330	0,177	7,527	0,000	***
childcare03	-0,001	0,001	-1,363	0,174	
preschool	0,002	0,002	1,038	0,300	
ln_inv_pc	0,126	0,038	3,320	0,001	**
urban	-0,008	0,006	-1,360	0,175	

Note: compiled by the authors.

The transition to the fixed-effects specification substantially alters the structure of statistically significant determinants. The gender wage gap (gwg) loses statistical significance ($p = 0.153$), indicating that a robust within-region effect is absent once unobserved regional heterogeneity is taken into account. Similarly, digitalization indicators (wic_it, ict_it, internet_it) and female unemployment (funemp) do not exhibit statistically significant effects in this specification.

Industrial employment (ind_emp: $\beta = 0.016$; $p < 0.01$) emerges as a significant positive determinant, suggesting that the industrial sector contributes to regional economic growth in

dynamic terms. Investment in fixed capital (ln_inv_pc: $\beta = 0.126$; $p < 0.01$) remains significant, as does the level of wages (ln_wage: $\beta = 1.330$; $p < 0.001$), which displays the largest coefficient magnitude among the regressors.

A negative and statistically significant effect is identified for the share of graduates (grad_emp: $\beta \approx -0.000$; $p < 0.001$). This may reflect structural characteristics of regions with a high concentration of educational institutions, in which short-term GRP growth does not necessarily increase in proportion to the number of graduates. Overall, the two-way fixed-effects model provides a more stringent assessment of within-region dynamics than the pooled specification, enabling a clearer separation between structural cross-regional differences and temporal effects.

To test the robustness of these findings, heteroskedasticity-robust standard errors of the HC1 type clustered at the regional level were additionally computed. Clustering accounts for intra-group error correlation and heteroskedasticity, thereby enhancing the reliability of statistical inference in panel data settings.

Table 5 presents the results from the two-way fixed-effects model with clustered robust standard errors.

Table 5. Two-way Fixed Effects with robust standard errors (HC1)

Variable	Estimate	Std_Error_HC1_cluster	t_value	p_value
gwg	-0,004	0,005	-0,796	0,427
wic_it	0,000	0,001	0,262	0,794
ict_it	-0,011	0,029	-0,378	0,706
agr_emp	-0,004	0,004	-1,015	0,311
ind_emp	0,016	0,010	1,689	0,093
grad_emp	0,000	0,000	-3,854	0,000
internet_it	0,001	0,001	1,094	0,275
funemp	-0,013	0,011	-1,170	0,243
ln_wage	1,330	0,228	5,821	0,000
childcare03	-0,001	0,001	-1,328	0,186
preschool	0,002	0,003	0,741	0,459
ln_inv_pc	0,126	0,067	1,893	0,060
urban	-0,008	0,010	-0,798	0,426

Note: compiled by the authors.

Following the adjustment of standard errors, the structure of statistical significance changes partially. The most robust determinant remains the level of wages (ln_wage: $\beta = 1.330$; $p < 0.001$), which exhibits a strong and positive effect on regional economic growth. The human capital indicator (grad_emp) retains a negative and statistically significant coefficient ($\beta \approx -0.000$; $p < 0.001$), confirming the stability of the identified relationship.

Industrial employment (ind_emp) and investment in fixed capital (ln_inv_pc) preserve their positive effects; however, their statistical significance declines to the 10% level ($p = 0.093$ and $p = 0.060$, respectively), indicating sensitivity of the estimates to the correction for intra-group correlation. The gender wage gap (gwg), ICT employment (ict_it), the share of women in ICT (wic_it), as well as indicators of digitalization, social infrastructure, and female unemployment, do not demonstrate statistically significant effects within the framework of within-region dynamics after controlling for fixed effects and clustering the errors.

These findings suggest that investment activity and income levels are the primary drivers of within-region growth, whereas gender and digital indicators appear less influential in short-term dynamics, even after strict control for individual and time effects. The coefficient of determination

(R^2 = 0.540) indicates that the model explains approximately 53.9% of the within-variation in the logarithm of gross regional product after accounting for regional and time effects. The adjusted R^2 (0.441) is somewhat lower, reflecting the inclusion of many fixed effects and regressors, yet it remains acceptable for panel models with a "strict" specification.

The F-statistic (F = 17.75, df1 = 13, df2 = 197) is statistically significant at $p < 2.22 \times 10^{-16}$, confirming the joint significance of the included explanatory variables. The reduction in R^2 relative to the pooled model is explained by the fact that the two-way fixed-effects specification captures only within-region temporal variation, eliminating cross-regional structural differences. Thus, the two-way fixed-effects model demonstrates statistical consistency and provides a more rigorous identification of the determinants of regional economic growth dynamics.

To identify typological differences in the structure of employment, the level of digitalization, and gender-related characteristics, a cluster analysis of the regions was conducted. The clustering procedure enabled grouping regions according to similarities in socio-economic and structural parameters, including the level of ICT employment, sectoral specialization, the gender wage gap, wage levels, and indicators of social infrastructure.

The clustering results indicate the formation of four stable groups of regions that differ in their models of economic development and the nature of women's participation in the labor market. The identified clusters reflect various combinations of digital, industrial, and agrarian characteristics, as well as differences in income levels and gender disparities.

Table 6 presents the composition of the clusters and their key characteristics.

Table 6. Typology of Kazakhstan's regions by employment structure, digitalization and gender characteristics

Cluster	Region	gwg	wic_it	ict_it	serv_emp	agr_emp	ind_emp	grad_emp
1	Almaty city, Astana city	21,4	44	4,47	80,8	0,571	18,6	35468
2	Aktobe, East Kazakhstan, Karaganda, Kyzylorda, Pavlodar, West Kazakhstan	28,9	45,9	1,27	60,9	14,6	24,5	16482
3	Akmola, Almaty, Kostanay, North Kazakhstan, Turkistan, Zhambyl,	16,6	41,5	1,07	54,6	30,7	14,7	8420
4	Atyrau, Mangystau	51,2	41,7	1,6	64,6	2,45	32,9	8533

Note: compiled by the authors.

The results of the cluster analysis allowed us to identify four stable types of regions, differing in the level of the gender gap, employment structure and degree of digitalization. The first cluster (Almaty and Astana) is characterized by the highest employment in ICT (ict_it = 4.47), the dominance of the service sector (serv_emp = 80.8%) and the minimum share of people employed in agriculture (0.57%). The gender pay gap is 21.4%, which is lower than in industrial and resource regions. The highest graduation rate is also recorded (grad_emp = 35,468), reflecting the concentration of human capital in the largest cities. The second cluster unites industrial regions with an average level of ICT employment (1.27) and a relatively high proportion of women in ICT (wic_it = 45.9%). The employment structure is characterized by a significant industrial share (24.5%) with moderate agricultural specialization (14.6%). The gender gap (28.9%) is higher than in the first cluster, indicating a more pronounced income differentiation.

The third cluster is mainly agricultural, with a high proportion of people employed in agriculture (30.7%) and a low level of industrial employment (14.7%). The level of ICT employment remains moderate (1.07), and the proportion of women in ICT is 41.5%. The gender gap (16.6%) is the smallest among all clusters. The graduation rate (8,420) is significantly lower than in clusters 1 and 2, reflecting a limited concentration of human capital. The fourth cluster includes resource-oriented regions with the highest gender wage gap (51.2%) and a high proportion of industrial employment (32.9%) with minimal agricultural specialization (2.45%). The level of ICT employment is 1.6%, and the proportion of women in ICT is 41.7%. The graduation rate (8,533) is comparable to that of the third cluster, indicating a limited educational concentration with high income differentiation. The resulting typology demonstrates the structural heterogeneity of regional development and allows for a deeper interpretation of the regression analysis results in the context of differences in economic models and gender involvement (Figure 4).

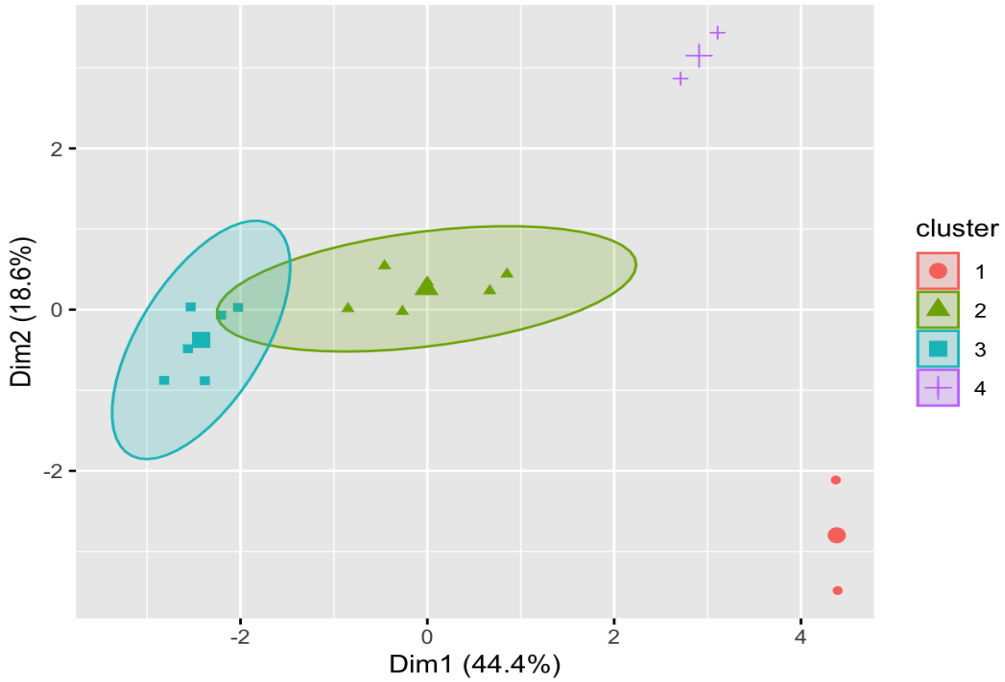

Figure 4. Results of clustering of regions by the k-means method (k = 4) in PCA.

The spatial locations of the points reflect the degree of similarity between the regions in terms of the totality of economic, structural, and gender characteristics. The differentiation of clusters confirms the stability of the obtained typology. The first cluster forms a separate group with pronounced values on the first component, indicating a specific model of economic development. The second cluster occupies a central position and is characterized by moderate values for both factors. The third cluster is shifted to the negative values of the first component, which reflects a different structure of employment and digitalization. The fourth cluster is located in the zone of high positive values for the second component, demonstrating a distinctive combination of income and gender characteristics. The cluster analysis confirmed the presence of pronounced structural heterogeneity of Kazakhstan's regional development in terms of digitalization, industry

specialization and gender characteristics of the labor market. The results of cluster analysis complement regression estimates, allowing us to interpret the identified dependencies in the context of typological differences across regions and to clarify the roles of gender and digital factors in shaping regional economic development.

5. Conclusion

The conducted research allowed us to empirically test five hypotheses put forward about the role of digitalization, gender indicators and structural factors in shaping Kazakhstan's regional economic growth in 2010-2024. The estimates obtained from a two-factor fixed-effects model with clustered standard errors allow us to draw the following conclusions.

Indicators of digitalization do not demonstrate a stable independent impact on GRP within intra-regional dynamics (H1 — not supported). Digital development primarily reflects the broader level of structural modernization of a region rather than functioning as an autonomous driver of short-term economic growth. This result refines interpretations regarding the expansion of economic opportunities through ICT (Mariscal et al., 2019) and the macro-level association between digital development and reduced inequality (Shah & Krishnan, 2024), suggesting that such relationships may not translate directly into within-country regional dynamics.

The direct intra-regional impact of gender indicators has not been statistically confirmed in the strict two-way fixed effects specification (H2 — supported). The significance of the gender wage gap identified in the pooled model disappears after controlling for regional heterogeneity, indicating that the observed differences are predominantly structural rather than dynamic in nature. This finding contrasts with cross-country evidence suggesting a reduction in gender inequality associated with digital development (Thanh et al., 2022; Shah & Krishnan, 2024; Tunçsiper, 2025) and underscores the importance of territorial context in shaping these effects (Zhao & Kuang, 2025).

The role of human capital demonstrates a more complex pattern (H3 — partially supported). The indicator of graduates per 10,000 population remains statistically significant across specifications; however, the direction of its effect differs between pooled and within-region estimates. While the pooled model suggests a positive association with economic growth, the two-way fixed effects results reveal a negative within-region coefficient. This divergence indicates that human capital contributes to cross-regional structural differentiation, yet its short-term intra-regional impact may reflect adjustment processes, spatial concentration of educational institutions, or delayed economic returns. The findings highlight the importance of distinguishing between between-region structural effects and within-region dynamics when interpreting the role of education in regional development.

The hypothesis concerning the positive role of structural and investment factors in economic growth receives empirical support (H4 — supported). Investments in fixed capital, wage levels, and, to a lesser extent, industrial specialization emerge as statistically significant determinants of intra-regional growth. These findings are consistent with studies emphasizing the importance of industry structure and institutional conditions in shaping regional development trajectories (Caragliu & Del Bo, 2025), as well as with research on labor market segmentation and the institutional conditioning of gender effects (Holth et al., 2017; Persson & Wallo, 2024).

The hypothesis of territorial heterogeneity reflected in distinct regional development models is confirmed by the cluster analysis (H5 – supported). Four stable types of regions are identified,

digital-service, industrial, agricultural, and resource-oriented, each characterized by specific combinations of employment structure, wage levels, and gender indicators. Spatial differentiation corroborates conclusions regarding the territorial modification of digital effects (Ay & Kılıç, 2023; Nguyen et al., 2025) and demonstrates that the realization of gender potential varies depending on the structural configuration of the regional economy.

The totality of the results supports the framework of structurally embedded digital transformation: the economic effects of digitalization are manifested indirectly through investment activity, industry specialization and human capital. This interpretation is consistent with the concept of a multi-level digital divide (Ogbo et al., 2021; Pham et al., 2025) and with the conclusion that removing infrastructure constraints does not guarantee reducing inequality (Zhao & Kuang, 2025).

The methodological contribution is to demonstrate the need to distinguish between cross-sectional structural differences and intra-regional dynamics when analyzing panel data, which corresponds to modern econometric approaches (Shah & Krishnan, 2024; Kabanov et al., 2024). Unlike most cross-country studies, the estimates obtained reveal the specifics of the intra-country effects of digitalization in conditions of pronounced regional asymmetry.

Applied implications point to the limitations of a policy focused solely on expanding digital infrastructure. Increasing women's economic involvement and narrowing gender gaps require a comprehensive structural transformation that includes investment, industry diversification, and human capital development. The inclusive effect of digitalization is realized only when it is integrated into a broader strategy of institutional and regional development.

Author Contributions: Conceptualization and theoretical framework, PK, GO; Methodology and research design, PK; Software, PK; Validation, GO; Formal analysis, GO; Investigation, PK, GO; Resources, GO; Data curation, PK, GO; Draft writing, PK, GO; Writing-review and editing, PK, GO; Visualization, PK, GO; Supervision, PK, GO; Project Administration, PK, GO; Funding acquisition, GO. All authors have read and agreed to the published version of the manuscript.

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Information about the authors

Peter Karácsony – PhD, Professor, Obuda University, Budapest, Hungary, email: karacsony.peter@uni-obuda.hu, ORCID ID: https://orcid.org/0000-0001-7559-0488
Gulbakhyt Olzhebayeva – PhD candidate, Almaty Management University, Almaty, Kazakhstan, email: g.olzhebayeva@gmail.com, ORCID ID: https://orcid.org/0000-0002-4964-2747

Авторлар туралы мәліметтер

Карачони П. – PhD, профессоры, Обуда Университеті, Будапешт, Венгрия, email: karacsony.peter@uni-obuda.hu, ORCID ID: https://orcid.org/0000-0001-7559-0488
Олжебаева Г. – PhD докторанты, Алматы Менеджмент Университеті, Алматы, Қазақстан, email: g.olzhebayeva@gmail.com, ORCID ID: https://orcid.org/0000-0002-4964-2747

Сведения об авторах

Peter Karácsony – PhD, профессор, Университет Обуда, Будапешт, Венгрия, email: karacsony.peter@uni-obuda.hu, ORCID ID: https://orcid.org/0000-0001-7559-0488
Олжебаева Г. – PhD докторант, Алматинский университет менеджмента, Алматы, Казахстан, email: g.olzhebayeva@gmail.com, ORCID ID: https://orcid.org/0000-0002-4964-2747