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DIGITAL TECHNOLOGIES AS A TOOL FOR IMPROVING THE QUALITY OF HIGHER EDUCATION

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Abstract. Digital transformation is one of the hallmark trends in the modern higher education sector, but there is an empirical ambiguity in its influence on the quality of higher education. The current study uses an unbalanced panel data for the analysis of digital transformation and the quality of higher education for 20 regions in Kazakhstan during the time period of 2012 to 2024. In order to incorporate the multivariable character of the studied subjects, a Digital Transformation Index and a Higher Education Quality Index are built through a principal component analysis, explaining the first principal components in total variance of 67.7% and 69.6%, respectively. The empirical approach employs fixed-effects panel equations, dynamic lag functions, non-linear equations, system GMM, and k-means clustering methods. Starting from fixed-effects panel equations, the baseline analysis finds that one unit increase in the digitalization index is related to a -0.12 standard deviation change in the quality of higher education in the short run, controlling for regional and time fixed effects. Moreover, dynamics verify that the negative impacts are retained for two periods, thereby confirming that adjustment costs are present. However, institution size variables, like the number of HEIs and enrollments in HEIs, display positive and significant coefficients. Non-linear estimation indicates a significant inverted U-shaped result, meaning that digitalization has a positive effect on education quality only up to a point, after which the marginal return turns negative. The System GMM supports the results and controls for endogeneity with

a high persistence level in education quality of approximately 0.50. Further analysis shows that digitalization increases graduate production but not gross enrollment, implying efficiency and not scale, while region-wise clustering indicates strong digitalization and quality concentration in urban agglomerations.

Keywords: Digitalization, Higher education quality, Panel data analysis, Non-linear effects, Regional disparities, Composite indices, Kazakhstan

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ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАР ЖОҒАРЫ БІЛІМ САПАСЫН АРТТЫРУДЫҢ ҚҰРАЛЫ РЕТІНДЕ

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Аннотация. Цифрлық трансформация қазіргі жоғары білім беру секторындағы негізгі үрдістердің бірі болып табылады, алайда оның жоғары білім сапасына ықпалы жөнінде эмпирикалық тұрғыдан бірмәнді қорытынды жоқ. Осы зерттеуде 2012–2024 жылдар аралығында Қазақстанның 20 өңірі бойынша цифрлық трансформация мен жоғары білім сапасының байланысын талдау үшін теңгерімсіз панельдік деректер пайдаланылды. Зерттелетін құбылыстардың көпөлшемді сипатын ескеру мақсатында негізгі компоненттерді талдау (principal component analysis) арқылы Цифрлық трансформация индексі және Жоғары білім сапасы индексі құрастырылды; сәйкесінше бірінші негізгі компоненттердің жалпы дисперсияны түсіндіру үлесі 67,7% және 69,6% құрады. Эмпирикалық тәсіл бекітілген әсерлер (fixed

effects) панельдік теңдеулерін, динамикалық лаг функцияларын, сызықтық емес теңдеулерді, System GMM және k-means кластерлеу әдістерін қамтиды. Бекітілген әсерлер моделінен басталатын базалық талдау цифрландыру индексінің бір бірлікке өсуі қысқа мерзімде жоғары білім сапасының -0,12 стандарттық ауытқуға өзгеруімен байланысты екенін, өңірлік және уақыттық бекітілген әсерлерді бақылау жағдайында, көрсетеді. Сонымен қатар динамикалық бағалаулар теріс ықпалдың екі кезең бойы сақталатынын анықтап, бейімделу шығындарының бар екенін растайды. Алайда институт ауқымын сипаттайтын айнымалылар, атап айтқанда ЖОО саны мен ЖОО-дағы білім алушылар контингенті, оң және статистикалық мәнді коэффициенттер көрсетеді. Сызықтық емес бағалау елеулі төңкерілген U-тәрізді тәуелділікті анықтайды: яғни цифрландыру белгілі бір шекке дейін білім сапасына оң әсер етеді, ал одан кейін шекті қайтарым теріс мәнге ауысады. System GMM нәтижелері бұл қорытындыларды қолдап, эндогенділікті бақылауға мүмкіндік береді; білім сапасының инерциясы (тұрақтылық деңгейі) шамамен 0,50 екенін көрсетеді. Қосымша талдау цифрландыру түлектер санының артуына ықпал ететінін, бірақ жалпы қамтуды (gross enrollment) арттырмайтынын айқындайды, бұл әсердің ауқымнан гөрі тиімділікпен байланысты екенін білдіреді. Өңірлік кластерлеу қалалық агломерацияларда цифрландыру мен сапаның айқын шоғырлануын көрсетеді.

Түйін сөздер: цифрландыру, жоғары білім сапасы, панельдік деректерді талдау, сызықтық емес әсерлер, өңірлік теңсіздіктер, құрастырмалы индекстер, Қазақстан

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ЦИФРОВЫЕ ТЕХНОЛОГИИ КАК ИНСТРУМЕНТ ПОВЫШЕНИЯ КАЧЕСТВА ВЫСШЕГО ОБРАЗОВАНИЯ

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Аннотация. Цифровая трансформация является одним из ключевых трендов в современном секторе высшего образования, однако в эмпирических исследованиях сохраняется неоднозначность в оценке её влияния на качество высшего образования. В настоящем исследовании используется несбалансированная панельная база данных для анализа взаимосвязи цифровой

трансформации и качества высшего образования по 20 регионам Казахстана за период 2012–2024 гг. Для учёта многомерного характера изучаемых явлений на основе метода главных компонент (principal component analysis) построены Индекс цифровой трансформации и Индекс качества высшего образования; доля объяснённой дисперсии первой главной компонентой составила 67,7% и 69,6% соответственно. Эмпирический подход включает панельные уравнения с фиксированными эффектами, динамические лаговые функции, нелинейные уравнения, System GMM и методы кластеризации k-means. Базовый анализ на основе модели с фиксированными эффектами показывает, что увеличение индекса цифровизации на одну единицу связано с изменением качества высшего образования на -0,12 стандартного отклонения в краткосрочном периоде при контроле региональных и временных фиксированных эффектов. Динамические оценки подтверждают, что отрицательные эффекты сохраняются на протяжении двух периодов, что указывает на наличие издержек адаптации. Вместе с тем переменные, отражающие масштабы институтов, такие как количество вузов и численность обучающихся в вузах, демонстрируют положительные и статистически значимые коэффициенты. Нелинейная оценка выявляет значимую перевёрнутую U-образную зависимость: цифровизация оказывает положительное влияние на качество образования лишь до определённого порога, после чего предельная отдача становится отрицательной. Оценки System GMM подтверждают результаты и позволяют контролировать эндогенность при высокой устойчивости качества образования (примерно 0,50). Дополнительный анализ показывает, что цифровизация увеличивает выпуск выпускников, но не влияет на валовой охват обучением, что указывает на рост эффективности, а не масштаба. Региональная кластеризация фиксирует концентрацию высокой цифровизации и качества в городских агломерациях.

Ключевые слова: цифровизация, качество высшего образования, панельный анализ данных, нелинейные эффекты, региональные различия, композитные индексы, Казахстан

Introduction. One of the most transformative institutional forces in modern higher education has been the phenomenon of digital transformation. Technological advancements in the area of information and communication, the use of digital platforms, and the increased application of data analytics in decision-making have brought deep-seated changes in the organization of teaching and learning activities, resource management, as well as the assessment of quality in higher education institutions. What is most noticeable is the extension of digital transformation from the support services core into teaching-learning and governing activities such as the delivery of the curriculum. Hence, the study of its implications for quality in higher education has become a pressing concern.

On the international level, information and communication technology is

viewed as an enabler of improvement in accessibility, effectiveness, and learning outcomes. Online learning platforms, virtual learning simulations, learning management systems, and AI-based learning systems are expected to increase malleability and adaptability in education. These have been facilitated by agendas of policy initiatives that have encouraged digitalization as an instrument of achieving inclusive growth and innovation. Nevertheless, there are signs emerging that, on the one hand, the correlation between digitalization and quality in education is by no means automatic, and, on the other, it even tends to be largely positive.

However, the onset of the COVID-19 pandemic further amplified the salience of this issue. The sudden shift to online and hybrid learning models proved to be a massive stress test for higher education systems across the world. Although technology helped in maintaining continuity in learning, it ironically revealed many inequities within and among institutions in terms of their technological preparedness and learning experiences of students. Thus, for most institutions, the sudden shift to online learning led to concerns not only about learning but also learning outcomes, declining assessment integrity, and learning depth.

Against this backdrop, there has recently been considerable literature that highlights the complex and potentially non-linear dynamics of digital transformation in education contexts. While initial digital investments may help improve learning outcomes through enhanced efficiency and access to knowledge, overextended or inefficient expansion of digital technologies in education could cause tensions in learning resources and potentially lower learning outcomes. Additionally, learning gains from digital transformations are also rather uneven in regional and higher education contexts. Metropolitan universities are likely to benefit disproportionately from digital transformations of higher education, whereas peripheral or less well-funded regions are likely to face higher transition costs for learning.

Though a vast amount of research has been carried out in the sector, especially in the fields of medicine, health, and professional education, certain gaps still exist. First, the majority of the available empirical evidence has been derived from case studies, cross-sectional studies, and institutional-level analyses, and thus it becomes difficult to observe adjustment processes dynamically. Second, there is a lack of studies investigating the complex factors of digitalization and education performance in a comprehensive manner by combining different factors into a composite indicator. Third, there is a dearth of studies focused on a comparative regional perspective on the factors of digitalization, taking into consideration issues of heterogeneity, persistence, and nonlinear effects, particularly in emerging and transition economies.

A particularly instructive case study for this purpose is offered by Kazakhstan. During the last ten years, this country has successfully developed its information and communication technology infrastructure and reformed its higher education sector, with strong regional differences in economic development and institutional capacity. Such a setting allows exploring the interplay of digitalization and higher

education structures in the context of irreversible change. Research on this problem is of considerable significance not only in terms of its pertinence to the development of Kazakhstani policies, but also in relation to theoretical conceptualization of digital transformation in higher education.

The contribution of this paper to the literature is a systematic, regionally disaggregated analysis of the nexus between digitalization and higher education quality in Kazakhstan during the period 2012–2024. A multidimensional approach is developed in this paper, using composite index construction, panel econometric modeling, dynamic and nonlinear specifications, and spatial clustering techniques. This framework allows for the identification of short- and medium-term effects, threshold dynamics, and regional development patterns often missed by previous studies.

The present research uses three related questions: the historical evolution of digitalization across regions; how such a relationship corresponds to the changes in quality of higher education over time. Does digitalization influence educational quality in a linear or nonlinear way, considering institutional capacity and unobserved heterogeneity? To what extent do regional disparities shape the outcomes of digital transformation in higher education?

Through answering these questions, this study expects to move away from a simplistic debate on the role of digitalization, on one hand, if it is an unmixed blessing, and on the other hand, if it is an intrinsic threat. This research expects to make evidence-based contributions on conditions favorable to the role of digitalization in negatively and positively impacting the quality of higher education.

Literature review. The digitalization process can now be identified as a new structural driver in the field of higher education, which influences teaching practices, the organization of institutions, and quality assurance systems. There is evidence that the integration of digital technologies changes not only teaching practices but also the allocation of learning resources and their outcomes in institutions and geographical locations. The use of digital technology in medical and health education has been found in research to widen the adaptability and availability of education but also strengthens reliance on the digital readiness of institutions (Han et al., 2019; Hao et al., 2021).

A few research works underpin the fact that technology advancement does not have an innate quality-enhancing process. On the contrary, its implementation depends directly on harmony between technological implementation and pedagogic and organizational capabilities. For instance, research by Chong et al. in 2021 demonstrated how crises accelerated technology implementation enhanced continuity of learning but highlighted inadequacies in faculty readiness and assessment validity. Again, Fedorchenko and Zaiiats' argument in 2025 demonstrated how AI and technology help in improving personalized learning only when it is integrated into a broader organizational plan and not as separate technologies.

Availability and maturity of digital infrastructure is a critical pre-condition to reaping the benefits of digitalization in terms of enhanced educational quality. The empirical literature reports that institutions with more developed digital infrastructure-those with access to reliable internet, digital learning management systems, and integrated platforms-exhibit more instructional continuity and higher levels of engagement on the part of students (Hassell et al., 2011; Wu et al., 2022). On the other hand, this uneven distribution creates structural inequities among institutions.

On the one hand, Hao et al. (2021) show that in nursing education, a lack of digital infrastructure in emergency transitions to online learning reduced perceived learning effectiveness and increased cognitive load among students. Similarly, Prats et al. (2016) provide evidence that advanced digital tools improve skill acquisition only under suitable institutional resources and faculty supervision. These could indicate that, at least in the initial stages, digitalization exerts pressure on educational quality in under-resourced environments, especially during rapid expansion.

Digital competence of lecturers and students is always a major mediator that appears in the relationship between technology adoption and outcomes. For example, a study by Behrends et al. in 2021 shows that interdisciplinary digital competence courses enhance teaching proficiency and innovation potential. Another example is a study by Seemann et al. in 2022 that showed digital health modules are a way of improving outcomes only if teachers have the appropriate digital teaching competencies.

Aminu et al. (2021) observe that the prediction of engagement with continuous medical education is very strongly predicted by digital competence, suggesting that the quality of education not only relies upon but also shapes the lifelong educational pathways of an individual. On the other hand, Mitra (2021) argues that the availability of digital devices such as tablets alone cannot improve outcomes in graduate medical courses. This provides evidence that the corrective effect of digital competence is more of a conditioning factor than an independent variable.

Digitalization opens new approaches in education, such as virtual simulation learning, virtual anatomy software, and artificial intelligence-assisted adaptive learning. On the scientific side, research shows that digital learning tools can foster better knowledge retention, problem-solving abilities, and engagement in learning when designed and delivered optimally. Wu et al. (2022) offer evidence that virtual simulation learning increases diagnosis and procedural skills in medical education for undergraduates. Quek (2024) also shows that digital anatomy tools improve learning abilities in understanding spaces. However, effectiveness in terms of pedagogy differs in settings. Neve, Ezekwuchendu, and Adelegan (2020) clearly support their observation, stating that a disparity between digital technology and learning goals leads to inefficiency in learning and frustration on the side of students. Rubleva, Amankul, and Beisenova (2023) further support this issue, stating that

digital technology leads to a perceived degradation of quality in teaching at first, in case there is no experience in digital teaching design on the side of the lecturer.

The COVID-19 pandemic had offered an unparalleled large-scale testing ground for digital higher education systems. Empirical investigations uniformly report that digital learning ensured instructional continuity but often at the cost of reduced engagement, quality of assessment, and perceived learning depth. Parveen et al. (2022) find that undergraduate medical students experienced declines in satisfaction and practical skill development during fully online instruction. Lawes-Wickwar et al. (2023) similarly report weakened student–patient and student–carer interaction in digital undergraduate medical education. Simultaneously, hybrid models appeared as more resilient options. It is demonstrated by Silva et al. (2022) that in pharmacy education, blended digital–traditional formats achieved better graduate outcomes when flexibility was combined with structured supervision. These findings suggest that any negative impact of digitalization on quality depends on how instruction is designed and not on the presence of digital tools as such.

Studies carried out in the health and nursing spheres, pharmacy, and surgery education fields of study offer intensive information on the processes through which digitalization shapes the quality of education. Kleib et al. (2024), in a scoping review publication, identify digital health education to improve accessibility and interactivity and to be integrated into the curriculum to promote competency achievement. Alowais et al. (2023) show that digital literacy knowledge acquisition in pharmacy education developments professional readiness and information management skills.

Quek et al. (2025) demonstrate that surgical technology enhances confidence in procedure skills, but simulation must be augmented by real practice. Hassell et al. (2011) offer formative data that pathology slides enhance assessment of competency but must be assessed within standardized frameworks. Taken as a whole, these studies underline that digitization is adding value to certain aspects of education but also creating new assurance issues.

A recent body of work illustrates nonlinear and geographically diverse implications related to digital transformation. Rubleva et al. (2023) illustrate threshold effects in educational digitalization, illustrating that while initial adoption is useful, rapid adoption can challenge institutional capabilities. Prats et al. (2016) illustrate diminishing marginal benefits for advanced digital technologies when human capital is weak. There are also spatial disparities. Empirical research has repeatedly confirmed that big cities and well-equipped institutions have more to gain from digitalization than others (Hao et al., 2021; Chong et al., 2021). This indicates that digitalization has the potential to widen the quality gaps of higher education among regions if appropriate capacity-building strategies are not pursued together with digitalization.

On balance, it seems that digitalization has complex and contextually nuanced impacts on higher education quality. On one hand, digital technologies are able

to improve learning efficiency and innovation in higher education. On the other hand, any rushed or uneven adoption of digitalization in higher education could lead to short-term deterioration in quality because of adjustment costs and digital competence gaps. Despite the abundance of sector-specific findings, there are few studies that have employed a comprehensive index and a panel analysis framework in a cross-regional comparison. This is partially because past studies have not considered the infrastructure size and quality of outcomes together as one econometric process in the context of higher education quality affected by digitalization. By and large, this is what the current study will address.

Materials and Methodology. The current research employs a broad quantitative design that seeks to reveal the structural, dynamic, and geographical impact of digital technology on the quality of higher education. The design of the study combines several methodologies that include the development of a multivariate index model for analysis. This approach helps in understanding the dynamic processes of digital transformations in a higher education system.

The empirical data uses an unbalanced panel structure, focusing on 20 regions in Kazakhstan during the 2012-2024 timeframe. This data is derived from official statistical sources for these regions, as it is more representative and serves as an important dimension, given the significant territorial differences in the readiness of higher education infrastructure and socioeconomic development.

La estructura del análisis se enfoca en tres dimensiones básicas:

(i) Digital Infrastructure and Access,

(ii) capacity and performance in higher education, and

(iii) regional heterogeneity over time.

This architecture facilitates an integrated analysis of digitalization effects on educating systems, which goes beyond correlation analysis and concentrates on causal relationships, adjustment processes, and distribution patterns.

Digitalization and the quality of higher education are inherently multidimensional phenomena. This makes it difficult to measure them using simple indicators. To overcome this problem, composite indicators are calculated using principal component analysis. This approach to handling dimensionality helps to extract the maximum amount of information from variables.

Let $Z_k it$ represent a vector of standardized indicators referring either to digital infrastructure or outcome variables in region ii at time tt. The composite index can thus be defined as formula (1):

$$Index_i t = \Sigma(\lambda_k \cdot Z_k it) \quad (1)$$

where:

λ_k - represents the factor loadings associated with the first principal component.

Second, before applying PCA, it is necessary to standardize all variables to cancel scale effects and give them an equal weightage. The prominence of the first

component in accounting for total variation further validates that the constructed indexes are self-consistent and can be used as macro-indexes for digitalization and higher education quality.

The Digitalization Index records accessibility and spread of information and communication technology, while The Higher Education Quality Index represents both the quantitative and qualitative aspects of learning intensity and output.

To analyze the effect of digitalization on the quality of higher education, panel regression models will be estimated. The suitability of panel data methods in this particular case is, inter alia, founded on their ability to properly adjust for individual heterogeneity. The econometric specification of the model is as formula (2):

$$HEQ_i t = \alpha + \beta \cdot DIG_i t + \gamma X_i t + \mu_i + \tau_t + \varepsilon_i t \quad (2)$$

where:

$HEQ_i t$ - denotes the higher education quality index;

$DIG_i t$ - is the digitalization index;

$X_i t$ - is a vector of control variables capturing institutional scale and capacity (such as the number of higher education institutions, student enrollment, and academic staff);

μ_i - represents region-specific effects, and τττt denotes time fixed effects.

Fixed effects models and their estimators are favored, as no bias exists with respect to time-invariant regional features, such as educational specialization, geographical conditions, and institutional tradition. The results obtained in random effects models serve as reference points.

Digital transformation processes are not likely to immediately influence the quality of higher education. Instead, the processes are coupled with learning costs and the adaptation of institutions in the pursuit of integrating digital transformations in teaching and governance. To capture the nature of the processes, the models are set with digital transformations with a lag in the estimates.

Moreover, persistence in higher education quality is directly tackled by dynamic modeling approaches. The use of lagged dependent variables captures the calendar or path-dependent properties of educational systems, where current performance tends to heavily depend on past performance.

The connection between digitalization and quality in higher education can be potentially nonlinear. Thus, although initial digital investment can strengthen access, productivity, and educational outcomes, overinvestment and incoherent digital expansion might create allocation inefficiencies, perhaps even quality deterioration. To check for such tendencies, a quadratic model is employed as a formula (3):

$$HEQ_i t = \alpha + \beta 1 \cdot DIG_i t + \beta 2 \cdot DIG_i t^2 + \gamma X_i t + \mu_i + \tau_t + \varepsilon_i t \quad (3)$$

This formulation makes it possible to detect threshold values above which the marginal effect of digitalization becomes negative. Non-linear estimation gives valuable information about optimal paths for digitalization and does not require constant marginal assumptions. Table 1 shows descriptive statistics.

Table 1 − Descriptive Statistics (2012–2024)

Variable	Obs	Mean	Std. Dev.	Min	Max
Digitalization index	214	0.000	1.646	−1.583	8.836
Higher education quality index	224	0.000	1.669	−1.535	6.251
Gross enrolment (%)	224	53.58	36.66	10.19	204.64
Students	230	30,884	36,924	1,310	201,988
Faculty	230	2,168	2,961	32	14,599

Table 1 presents descriptive statistics for the key variables. The digitalization index and higher education quality index are standardized with a zero mean but show considerable dispersion, which points to very significant regional inequality in these areas. Gross enrolment goes from 10% to more than 200%, reflecting the concentration of higher education institutions in big urban agglomeration centers. Similarly, student numbers and faculty size demonstrate wide variation, underlining strong spatial heterogeneity across higher education systems in regions.

These patterns underscore the need for panel models controlling for unobserved regional heterogeneity. Figure 1 displays the national dynamics of the composite index of digitalization and the higher education quality index, over the period 2012–2024.

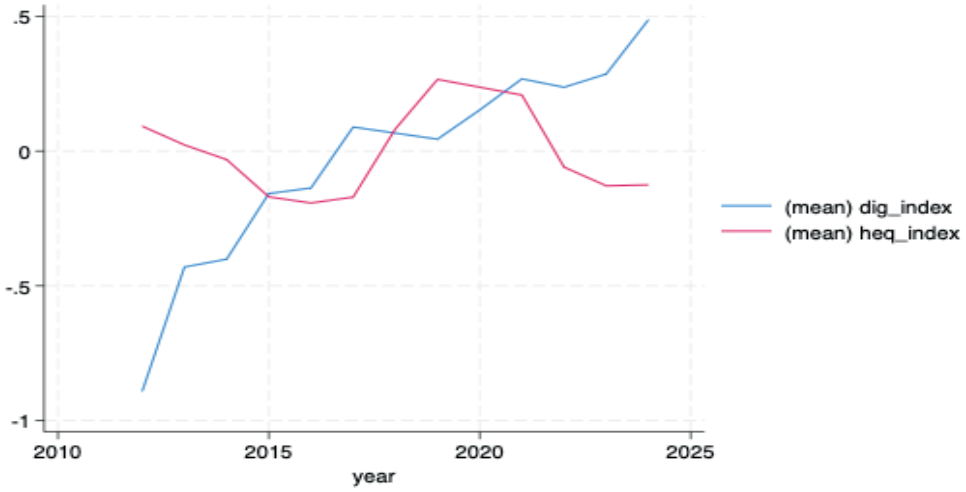

Figure 1 − National trends in digitalization and higher education quality

Both series show a strong positive trend, especially in the period that followed 2016, symbolizing the tremendous rate of expansion of digital infrastructure and the

gradual enhancement of higher education capacity in different regions. However, there are discrepancies in both series because the rate of enhancement in digital transformation is steeper in the latter years compared to the enhancement in higher education quality, assuming that there is no direct relationship between digital change and higher education performance. This assumption stimulates further econometric study of digital change and higher education quality in different regions of the globe.

There are two sources of potential endogeneity: reversed causality, measurement error, and the presence of uncontrolling variables. Regions with better educational quality could be more attractive to digital investments, or there could be a respective reaction to development dynamics. In order to address these problems, a robustness check is done using a system GMM estimator due to the dynamic nature of the model. This estimator is used for its ability to correctly handle potentially endogenous variables by using their lags as instruments.

Validity of the model results is checked by conventional diagnostic tests such as those for the presence of serial correlation and Over-Identifying Restriction Statistics. Further robustness tests would be to verify that the results are not sensitive to the choice of dependent variable and/or the structure of the lagged variables.

To round out the econometric analysis, an unsupervised clustering analysis is conducted to uncover horizontal disparities in digitalization and quality in higher education. K-means clustering analysis is conducted using standardized values from the comprehensive indices in the final year. K-means clustering analysis groups regions into homogeneous categories based on their structural properties, facilitating inter-group comparisons.

The result obtained from the clustering analysis helps in understanding the problem in a geographical way, and this result facilitates the Process of determining the leaders, transition, and laggers.

By combining the methods of constructing composite indexes, panel econometrics techniques, dynamic models, non-linear analysis, and cluster analysis in space, this proposed methodology allows for a multi-dimensional assessment of digitalization in higher education institutions in order to achieve a robust empirical basis for digital education policy-making.

Results. This section presents empirical results with respect to the nexus of digitalization and higher education quality across regions in Kazakhstan during the period 2012–2024. The analytical sequence includes the construction and validation of composite indices of digitalization and higher education quality by means of principal component analysis, followed by descriptive evidence on regional dynamics and dispersion. Fixed-effects panel regressions yield core results that are further extended into dynamic and nonlinear specifications in order to incorporate adjustment processes and threshold effects. System GMM estimations address potential endogeneity and persistence in educational outcomes. Regional heterogeneity was tested via k-means clustering. These results combined provide

a comprehensive assessment of short-term, dynamic, and spatially differentiated effects stemming from digital transformation on the quality of higher education.

Table 2 − Construction of Composite Indices (Principal Component Analysis)

Panel	Component	Eigenvalue	Variance explained (%)	Cumulative (%)
A. Digitalization Index	PC1	2.709	67.73	67.73
	PC2	0.929	23.21	90.94
	PC3	0.296	7.40	98.34
	PC4	0.066	1.66	100.00
B. Higher Education Quality Index	PC1	2.786	69.64	69.64
	PC2	0.999	24.96	94.61
	PC3	0.168	4.20	98.81
	PC4	0.048	1.19	100.00

Panel C. Component Loadings (PC1)

Variable	Digitalization	HE Quality
Internet users	0.203	–
Organizations with Internet	0.568	–
Computers	0.585	–
Fixed Internet	0.543	–
Gross enrolment	–	0.564
Graduates	–	0.579
Students	–	0.587
Faculty per 1,000	–	0.046

Table 2 above shows the results of the principal component analysis employed to derive the Digitalization Index and the Higher Education Quality Index. Panel A illustrates that the first principal component of the digitalization index captures 67.7% of the total variance and has high loadings correlated with the availability of Internet access among organizations, the availability of computers, as well as fixed Internet subscriptions. Panel B reveals that the first component captures 69.6% of the total variance in the higher education quality index and is primarily correlated with student enrollment, graduates produced, as well as gross enrollment rates.

Panel C verifies that both indices are statistically consistent and conceptually coherent, reflecting multi-dimensional characteristics of cyberspace infrastructure and educational performance. The dominance of the first component in both indices confirms the appropriateness of single indices in the econometric analysis. Table 3 shows baseline panel estimates of higher education quality.

Table 3 − Baseline Panel Estimates of Higher Education Quality

Dependent variable: Higher Education Quality Index

Variable	FE (1)	FE + Year FE (2)	RE + Year FE (3)
Digitalization index	−0.079**	**−0.121***	**−0.144***
	(0.038)	(0.030)	(0.024)
HEIs	0.063***	0.052***	0.058***

Students	0.000024***	0.000023***	0.000026***
Faculty	n.s.	0.000059**	0.000101**
Year FE	No	Yes	Yes
Observations	214	214	214
Regions	20	20	20
Within R^2	0.660	**0.759**	0.755

Table 3 reports the baseline panel regression results, where the dependent variable is the index of higher education quality. Across all specifications, the index of digitalization enters as significantly negative. For the preferred specification that includes year fixed effects (Column 2), a one-standard-error increase in digitalization is related to an index decline in the quality of education by 0.12 standard deviations.

By contrast, the structural variables, represented by the presence of higher education institutions and enrollments, positively and significantly affect the outcome. Faculty number becomes significant when year effects are controlled, and this suggests that human capital can positively influence quality enhancements.

These results indicate a possible initial pressure exerted on the education system in a rapidly expanding digital environment, perhaps because of adaptation costs, mismatch, and unbalanced integration of digital technology in learning activities. Figure 2 shows relationship between digitalization and education quality (FE-based).

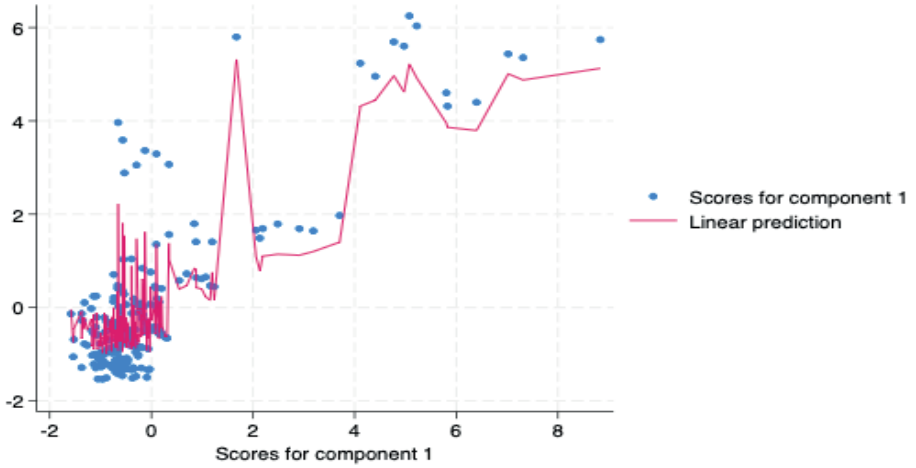

Figure 2 − Relationship between digitalization and education quality (FE-based)

Figure 2 depicts the correlation between digitalization and the quality of higher education using fixed effects. The scatter plot with a linear prediction line indicates a negative correlation between the digitalization index and the education quality index, notwithstanding the region's fixed, time-invariant attributes. The visual

representation is in agreement with the baseline panel regression result. Figure 3 shows coefficient plot from fixed effects model.

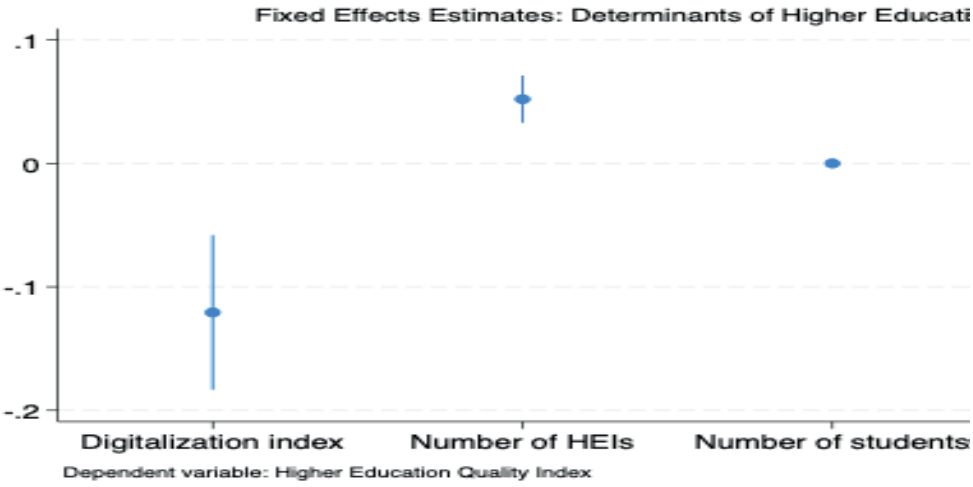

Figure 3 − Coeffi cient plot from fi xed effects model

Figure 3 displays a coefficient plot with 95% confidence intervals of the fixed effect model. This coefficient plot emphasizes the negative and significant effect of digitalization on the quality of higher education in comparison to the positive effect of institutional size variables like the number of higher education institutions and total number of enrolled students. This plot allows comparison of effect values across variables. Table 4 shows dynamic effects of digitalization.

Table 4 − Dynamic Effects of Digitalization (Dependent variable: Higher Education Quality Index)

Panel	Variable	Coefficient
A. One-lag FE	L.Digitalization index	−0.136*
	HEIs	0.073***
	Students	0.000022***
B. Two-lag FE	L1.Digitalization index	−0.098*
	L2.Digitalization index	−0.108*
	HEIs	0.081***
	Students	0.000025***
	Faculty	−0.000079*

In order to capture the lagged effects, Table 4 includes fixed effects models with lagged digitalization variables. In Panel A, it is observed that the one-period lag of digitalization is still negatively significant, with a coefficient of -0.136. Panel B further confirms that the first and second-order lag effects are still negatively significant but declining.

These results show that the non-positive association between digitalization and education quality is not of purely contemporaneous form but is also of longer-term dimensions. However, the presence of persistent positive coefficients for HEIs and number of students indicates that size and access have further reduced the impact in the medium term. Figure 4 illustrates predictive margins for lagged digitalization indicators with 95% confidence intervals.

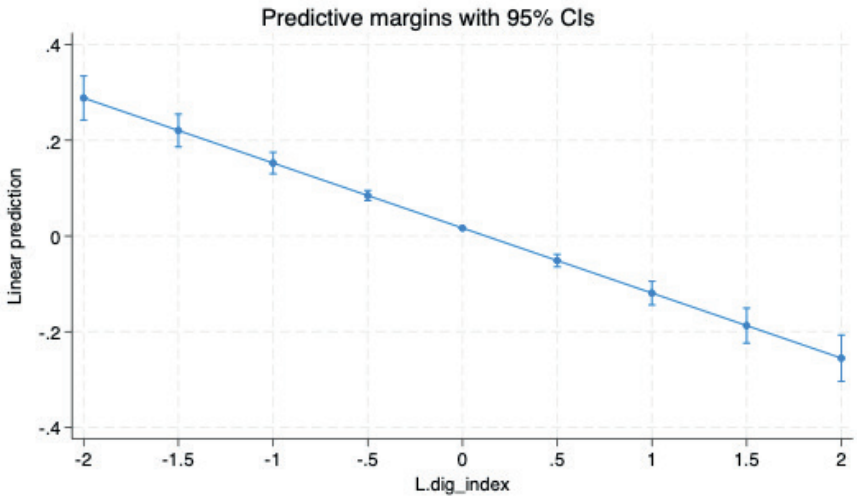

Figure 4 − Lagged effect of digitalization on education quality

This figure shows that the negative effect of digitalization in relation to quality in higher education is persistent in nature and captures delayed adjustment effects. The fall in predicted values establishes consistency in dynamic regression analysis results. Table 5 investigates non-linearities and includes squared values of digitalization in regressions.

Table 5 − Non-Linear Effects of Digitalization

Variable	FE estimate
Digitalization index	0.064
Digitalization²	−0.023*
HEIs	0.030***
Students	0.000028***
Faculty	n.s.
Within R^2	0.793

Note: Evidence of an inverted U-shaped relationship.

The presence of a strong positive linear term, in combination with a strong negative and significant quadratic term, clearly indicates the presence of an inverse U-shaped relation. This suggests that digitalization contributes positively within a certain range of higher education quality, and any further incremental increases

result in diminishing and possibly negative returns. The model's within R^2 of 0.79 indicates strong explanatory power, reinforcing the robustness of the non-linear specification. Figure 5 reports predictive margins with 95% confidence intervals derived from the non-linear specification.

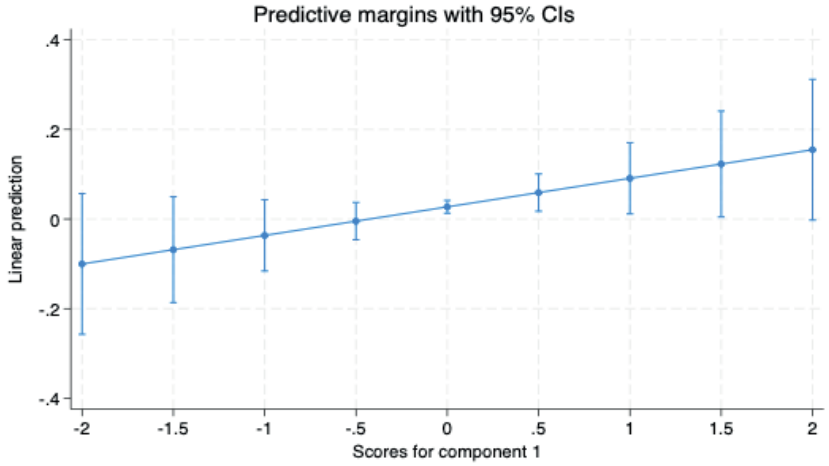

Figure 5 − Non-linear effect of digitalization (marginal effects)

Figure 5 shows an inverted U-shaped relationship between digitalization and the quality of higher education. While in the lower regions an increase in digitalization is related to an improvement in the quality of education, after a certain point the additional expansion of digitalization has a marginal effect of diminishing and negative returns. Table 6 contains the estimates from the dynamic system GMM approach that takes care of the issue of endogeneity and persistence in the quality of higher education.

Table 6 − System GMM Estimates

Dependent variable: Higher Education Quality Index

Variable	Coefficient
L.Higher education quality	0.503*
Digitalization index	−0.222*
HEIs	n.s.
Students	0.000025*
Faculty	n.s.

Diagnostics

Test	p-value
AR(1)	0.037
AR(2)	0.074
Hansen	0.989
Sargan	0.193
Instruments	23

This confirms that the lagged dependent variable is positive and highly significant, a fact that documents strong path dependence in regional education systems. The impact of digitalization remains negatively associated with education quality even after instrumenting, whereas student enrollment still exerts a positive effect. Model diagnostics provide support for the validity of our estimates: the Arellano-Bond test for second-order serial correlation does not reject the null of no serial correlation, while the Hansen test has a p-value well above conventional levels, indicating appropriate instrument specification. Table 7 extends our GMM estimates to several alternative dependent variables.

Table 7 − Effects on Alternative Higher Education Outcomes

Panel	Dependent variable	Digitalization (lagged)
A	Gross enrolment	−6.55*
B	Log graduates	0.083*
C	Faculty per 1,000 students	n.s.

The lagged digitalization index leads to a significant decrease in the gross enrollment rate, which may be an indication of crowding-out or substitution effects. However, graduate output is a positive factor, which indicates an increase in the efficiency of completion or throughput. Additionally, there are no statistically significant effects on faculty intensity, which means digitalization mostly affects through size and performance. Lastly, Table 8 presents the summary of the k-means clustering analysis performed for the year 2024.

Table 8 − Regional Clusters of Digitalization and HE Quality (2024)

Cluster	Number of regions	Interpretation
1	10	High digitalization – high HE quality
2	3	Medium transitional
3	7	Low digitalization – low HE quality

Regions are categorized into three different groups: High Digitalization-High Quality, Medium Transitional, and Low Digitalization-Low Quality. The regional location in the clusters shows clear stratification and proves previous research regarding imbalances in “digital and educational development.” Figure 6 represents the regions in different groups to emphasize that “high-quality” regions are centralized in metropolitan regions and industrial areas, making the periphery “structurally disadvantaged.”

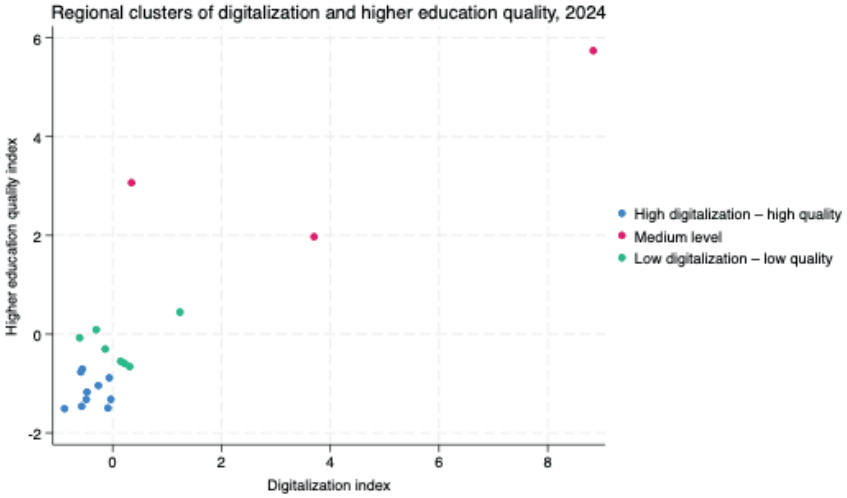

Figure 6 − Regional clusters of digitalization and higher education quality, 2024

In figure 6, results of k-means clustering of 2024 are depicted. A region is classified into three groups according to high, medium, and low regions of digitalization and quality of higher education. In figure 6, it may clearly be noted that regions near metropolitan regions and industrial areas are highly digitalized and have high quality in education, and regions at the periphery have low values in all parameters.

Discussion. This research work offers an exhaustive empirical analysis of the interlinkage between the process of digitalization and the attrition or augmentation in the quality of higher education based on regional panel data evidence from Kazakhstan from 2012-2024. This study is based upon the integration of index construction techniques and its application with the use of panel econometric analysis techniques in order to emerge with effective results.

There are a number of important findings from the results. Firstly, there has been a steady rise in the level of digitalization and higher education quality at the country level. This has happened due to increased efforts by countries to develop digital infrastructure. Notably, while there has been a broad-based acceleration in digitalization, especially from 2016, there has been a relatively slower pace in higher education quality. This goes to show that there may not be a direct link between digitalization and higher education quality.

Second, the baseline panel model consistently shows a negative relationship between the digitalization index and the overall quality of higher education after correcting for unobserved regional heterogeneity as well as correlated time fixed effects. In the preferred fixed-effects model, the digitalization index is shown to have a negative impact in the short run on the composite quality index. However,

the number of higher educational institutions, the number of students enrolled in higher education institutions, and the number of academic staff have a positive and significant impact. These findings imply that the accelerated digital growth could have created transition costs for the higher education sector. Digitalization in this case can be interpreted as a force that disrupts the higher education sector in the transitional phase.

Third, from the dynamic analysis, one finds that these impacts are not of a contemporaneous nature. The lagged digitalization variables are negative and significant, and therefore, adjustment takes place in more than one period. The fact that the negative lagged effects are persistent indicates that institutional learning, faculty adjustment, and changes in the curriculum take time to occur. However, the fact that the positive and stable effects of institutional scale remain in dynamic models indicates that capacity and access have a stabilizing effect in offsetting the negative impacts of technological change on higher education institutions.

Fourth, non-linear results are significant for understanding what digitalization-quality relation actually is because they show that digitalization has indeed augmented higher education quality until it reaches saturation beyond which marginal returns are either decreasing or even negative. Thus, it has managed to address opposing trends of literature that are differs in recognizing both sides of digital change impact. It has been seen that digital technologies work better when they are implemented in phased manner and in moderation because their implementation at saturating rates could lead to dispersion of quality in institutional resources and also overwhelm learning because of lack of proper governance of digital expansion.

Fifth, robustness tests via system GMM estimation validate the results while accounting for potential endogeneity issues. The persistence in the quality of higher education is a strong indication that education systems are path-dependent, with the ability of institutions being a function of previous performance. Despite this persistence and while accounting for digitalization, the negative relationship persists, thereby supporting that digital transformation has non-Trivial adjustment costs.

Lastly, through the analysis of alternative scenarios, the study discovers varying effects of digitalization on performance factors for higher education institutions. Although lagged digitalization is found to have an inverse effect on the gross enrollment rate in higher education institutions, there is a positive effect on the number of graduates, signifying an increase in efficiency in graduating rather than expanding access to higher education institutions for broader segments of the population. Failure to obtain significant results on faculty intensity, too, indicates that the causal factor lies along channels not related to staffing.

Finally, it is clear from the regional clustering analysis that there is marked spatial stratification in both digitalization and higher education quality. The regions cluster into distinct groups with high, medium, and low levels of the two dimensions,

with leading regions concentrated in metropolitan and industrial centers. Peripheral regions remain structurally disadvantaged, further underlining apprehensions that, unless matched by appropriate policy intervention, digital transformation may widen entrenched regional inequalities.

Conclusion. Taken together, these findings have important policy implications. Digitalization needs to be seen not as an end in itself but as part of a broader institutional transformation strategy. Investments in digital infrastructure need to go hand in hand with faculty training, pedagogical innovation, governance reform, and region-specific capacity building. Policymakers should pay particular attention to sequencing and thresholds, ensuring that digital expansion aligns with institutional readiness to avoid short-term quality deterioration. Moreover, addressing regional disparities requires differentiated approaches that support lagging regions in building both digital and educational capacity.

From the viewpoint of academic literature, this study provides systematic evidence on digitalization impacts on the quality of higher education through various dynamic, non-linear effects, and heterogeneous spatial patterns. It has also shown in detail the value of composite indices and longitudinal regional analysis for capturing complex transformation processes. Future research might extend this framework by incorporating micro-level institutional data, exploring field-specific heterogeneity beyond health and professional education, and looking at the long-term equilibrium effects of the digital transformation when adjustment processes have matured.

Conclusively, digitalization is both an opportunity and a challenge for higher education systems; its ultimate impact on quality depends critically on institutional capacity, temporal adjustment, and regional context. Understanding and managing these dimensions requires the changes needed to tap digital technologies in support of sustainable and inclusive higher education development.

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