International Journal of Technology
http://ijtech.eng.ui.ac.id

Research Article

Sustainable Development of Human Capital and Digital Technologies in Armenia as a Driver of Socio-Economic Consolidation

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Abstract: This study evaluates Armenia's human capital's sustainable development and its macroeconomic role in socioeconomic consolidation over the period 2000–2024. A six-block composite Human Capital Sustainability Index (HCSI) is constructed to address gaps in integrated diagnostics and is validated using PCA and clustering. The index rises from 0.26 in 2000 to 0.68 in 2023, followed by a correction to 0.60 in 2024, while GDP per capita increases from USD 1,229 to USD 5,378. Synchrony is high: the correlation between HCSI and income is 0.97, and a Granger causality test indicates an "HCSI → income" effect with a two-year lag ($p = 0.037$). A three-phase trajectory is identified—early stage (2000–2006), transition (2007–2015), and a new cycle (2016–2024)—with income acceleration emerging once HCSI reaches or exceeds 0.60. Digitalization is the principal transmission channel. The share of internet users reaches 80% in 2023, ICT services exports peak at 28.86% in 2020 and stabilize at 18.87% in 2023, and the diffusion of digital technologies supports productivity-enhancing reallocation. The innovation block remains a bottleneck, with R&D expenditures hovering between 0.18% and 0.21% of GDP. The economic implication is a strengthened contribution of human capital to productivity growth and export diversification, notably through information and communications technology (ICT) and other high-value-added services. Policy priorities include scaling digital skills and broadband infrastructure, harmonizing qualification frameworks across sectors, co-financing applied R&D and university-industry projects, lowering mobility barriers for skilled labor domestically and in adjacent markets, and developing interoperable digital platforms for cross-border service delivery. This package raises income resilience, dampens shocks, and supports a stable path of human capital-led growth.

Keywords: Cluster analysis; Digitalization; Human capital; Principal component analysis

1. Introduction

In contemporary economics, human capital (hereafter HC) is regarded as one of the key drivers of sustainable development and long-run growth. Investments in education, health, skills, and knowledge accumulation increase productivity and international competitiveness (Becker, 1993; Schultz, 1961). Armenia combines high educational coverage and near-universal adult literacy with demographic contraction and institutional constraints on the efficiency of social spending, which increases the sensitivity of development outcomes to the quality of human-capital governance and coordination mechanisms.

Empirical studies on Central Asia and the Caucasus confirm that education and capital investment sustainably support economic growth, whereas institutional quality effects remain heterogeneous across countries and periods. Such results have been demonstrated using unit-root

https://doi.org/10.14716/ijtech.v17i2.8258
Received September 2025; Revised December 2025; Accepted January 2026

and co-integration approaches, including the Pedroni and Kao tests and the FMOLS and DOLS estimators (Tleppayev et al., 2025). Integral aggregation approaches have been increasingly applied to represent HC as a multidimensional system, which improves cross-country comparability and enables the decomposition of contributions from education, health, and labor-market components (Kulzhanova et al., 2019). Migration processes are frequently interpreted within a social-investment framework, in which educational and labor mobility mitigate short-term imbalances but may reinforce national labor markets' external dependence (Andronova and Ryazantsev, 2023). For Armenia, ILCS-based estimates indicate that after 2015, the incomes of households sending migrants to Russia were 6%–11% higher, while the income gap relative to non-migrant households narrowed from about 6% to about 2% under a difference-in-differences design (Oksinenko, 2023). Simultaneously, small open economies face persistent barriers to trade in services related to licensing, logistics, fiscal regimes, and cultural constraints, which limit the domestic monetization of accumulated HC (Hakhverdyan et al., 2025).

Digital transformation opens additional technological channels for improving human-capital governance through big data analytics, artificial intelligence, distributed ledgers, RFID technologies, and satellite monitoring (Vovchenko et al., 2022). Armenia, however, continues to exhibit a pronounced digital divide. Distance from Yerevan and household income are significantly associated with ICT usage, as captured by the DTUI index, indicating uneven access to digital infrastructure and skills (Arion et al., 2024). Recent empirical literature links HC and digitalization with welfare and productivity outcomes while emphasizing the heterogeneity of effects and complex transmission mechanisms. For Central and Eastern European countries in the EU, digitalization components and HC jointly correlate with population welfare under fixed-effects panel specifications, yet the magnitude differs across countries and time windows (Grigorescu et al., 2021). Development-oriented perspectives also argue that digital transformation may widen inequality unless access, skills, and capability upgrading advance jointly, which makes the human-capital channel conditional on inclusive diffusion (Qureshi, 2023). Evidence for emerging economies suggests that ICT deepening can partly offset structural drags on productivity growth, such as informality, but the moderating effect remains modest and depends on complementary skills and infrastructure (Erumban, 2024). Time-varying analyses further indicate regime sensitivity, where digitalization can act as a net shock transmitter to HC and output, implying nonlinear dynamics in the linkage (Huyen et al., 2024).

Within the context of multilateral economic cooperation, digitalization interacts with innovation, institutional quality, and structural reallocation, shaping the ability of small economies to alleviate resource and development constraints and strengthen sustainable growth trajectories (Zheng et al., 2024). Cross-country comparisons across the post-Soviet space further reveal asymmetric linkages between environmental security and HC, which increases the analytical value of mixed diagnostic and typologizing methods (Demidova et al., 2021). Armenia's external economic orientation has followed a pendulum-like pattern of integration vectors, affecting regimes of accumulation and utilization of HC (Vasilyan, 2016), while sanctions conditions and the evolving sustainability agenda intensify the need for coordinated, digitally enabled policy responses (Yurova, 2023).

As a small economy, Armenia faces concentrated demographic pressures. The population declined from approximately 3.06 million in 2010 to less than 2.97 million in 2018, while the total fertility rate remains close to 1.6. By 2050, the proportion of the population aged 65 and over is projected to exceed 22%, alongside the increasing out-migration of working-age cohorts. High positions on international "brain drain" indicators indicate underutilization of skills within the domestic economy. Public expenditure on education fluctuates around 2.5%–3.0% of GDP, amounting to approximately 2.7% in 2020 and roughly 2.5% in 2022, which remains below the levels observed in larger regional peers. Institutional quality becomes a decisive factor determining the return on each additional unit of social spending under these conditions. Although free labor movement in adjacent markets and remittance inflows temporarily mitigate labor-market pressures, they may also entrench external dependence without resolving structural constraints on domestic value creation. Despite formal market openness, the rising complexity of non-tariff barriers in services further restricts the conversion of HC into value added (Hakhverdyan et al., 2025).

Digital platform solutions, conceptualized as governed transformational circuits, offer potential instruments for reducing regulatory asynchrony, information asymmetry, and spatial fragmentation. In this domain, institutional and techno-organizational architectures encompass algorithmic standard-setting, fiscal-redistributive mechanisms, cognitive feedback systems, digital twins, and clustering metrics that support digital interoperability and spatial coordination (Rodionov et al., 2025, 2025a). Such configurations enhance the steerability of HC through data standards, KPI-based monitoring, and scenario-driven competency mapping, aligning HC management practices with the logic of a developmental-state approach to digital public infrastructure.

Despite the growing evidence on the HC–digitalization nexus, Armenia-focused research remains fragmented across isolated indicators and partial channels. Long-horizon assessments often examine education, health, labor, innovation, and digitalization indicators separately, constraining subsystem-level interpretability in sustainability diagnostics. Empirical designs also rarely operationalize digitalization as a measurable transmission channel that converts accumulated capabilities into income and productivity in a small open economy, although recent studies report systematic associations between HC, digitalization, and welfare outcomes with heterogeneous magnitudes across institutional contexts (Grigorescu et al., 2021), emphasize inclusiveness constraints of digital transformation (Qureshi, 2023), and show that ICT can only partially mitigate structural frictions without complementary skills and infrastructure (Erumban, 2024). In addition, the lag structure and potential regime dependence of the HC–income linkage remains insufficiently tested within a unified national framework, while time-varying evidence suggests nonlinear and state-dependent interactions between digitalization, HC, and output (Huyen et al., 2024).

Based on this comparison between the Armenian case and the dominant empirical designs in prior studies, three research gaps are identified. Studies focused on Armenia often treat education, health, labor, innovation, and ICT indicators separately, which limits the integration of long-horizon diagnostics. Digitalization is rarely operationalized as a measurable transmission channel from capabilities to income. Lag structure and threshold behavior in the HC–income linkage remain weakly tested in a unified national framework.

The method selection follows these gaps. This study constructs a six-block composite Human Capital Sustainability Index (HCSI) for Armenia over 2000–2024 with subsystem decomposition. The block space is validated using PCA and K-means to identify regimes. VAR and Granger causality tests assess lagged directionality. The proposed design integrates digitalization indicators into the block architecture as a central transmission channel linking HC accumulation to income formation and productivity dynamics, which supports subsystem bottleneck diagnostics, window identification for sustainable development, and empirically grounded benchmarks for technology-informed policy coordination within Armenia and adjacent markets.

2. Materials and Methods

2.1 Data set and indicator system

The method selection follows the stated research gaps. Composite measurement provides integrated long-horizon diagnostics. The regime structure in the six-block space is validated by PCA and K-means. VAR and Granger causality tests were used to assess lagged directionality. The empirical base comprises annual observations for the Republic of Armenia over 2000–2025 on twenty indicators of HC and the socio-economic environment. For a subset of indicators, 2025 values are available as preliminary flash estimates. When a complete series is required, the analytical cutoff is 2000–2024, yielding $T = 25$ years. Variables are grouped into six thematic blocks — Education, Health, Innovation, Digitalization, Demography and Labor Market, and

Economy — which together form a balanced representation of inputs, stocks, outcomes, and technology-enabled channels.

Let $X_t = (X_{1t}, \ldots, X_{20t})$ denote the vector of the raw values in year t Table 1. Note: Block codes are defined as follows: A Education, B Innovation, C Digitalization, D Demography and Labor Market, E Health, F Economy. “Inverted” denotes indicators with adverse directionality that are transformed so that higher values correspond to better performance.

Table 1 The indicator system and block structure

Code	Block	Indicator	Role in the model
X1	A	Public expenditure on education, percent of GDP	Investment intensity, input
X2	A	Tertiary education gross enrollment, percent	Depth of skills formation, stock proxy
X3	A	Upper secondary enrollment, percent	Skills and literacy base
X4	A	Primary enrollment, percent	Minimum educational provision
X5	A	Adult literacy, percent	Final literacy, outcome
X6	B	R and D expenditure, percent of GDP	Investment in knowledge and technology
X7	B	Scientific publications, count	Research output
X8	B	Resident patent applications, count	Knowledge commercialization
X9	B	High-tech exports, USD	Technological specialization
X10	C	Internet users, percent of population	Household digital inclusion
X11	C	ICT services exports, percent of services exports	Digital component of the external sector
X12	C	Mobile subscriptions, per 100 inhabitants	ICT infrastructure density
X13	D	Total population, persons	Scale of human resources
X14	D	Share of population ages 15–64, percent	Employment and dependency potential
X15	D	Female labor force participation, percent	Gender inclusion
X16	D	Youth unemployment, percent	Risk of skills degradation, inverted
X17	E	Life expectancy at birth, years	Health system outcome
X18	D	Crude birth rate, per 1,000	Population reproduction and burden
X19	E	Under-5 mortality, per 1,000	Perinatal care quality, inverted
X20	F	GDP per capita, constant USD	Economic outcome and resource base

The block architecture serves three purposes. First, it limits the dominance of mass indicators, such as population, over intensive indicators, such as literacy or enrollment. Second, the block structure supports interpretable dynamics by organizing the system into stable HC subsystems. Third, it enables multivariate methods in a low-dimensional six-block index space. Digitalization plays a central role because X10–X12 proxy access, infrastructure, and knowledge-intensive service externalization, thereby enabling technology-based transmission from capabilities to incomes.

Pre-processing:

1. The pointwise gaps are linearly interpolated at an annual frequency.
2. Indicators with adverse directionality are inverted, for example, X16 youth unemployment and X19 under-5 mortality.
3. The interquartile-range rule controls outliers: observations outside $[Q_1 - 1.5 \cdot IQR, Q_3 + 1.5 \cdot IQR]$ are winsorized to the bounds.

4. X20 GDP per capita is deflated to a constant USD to reduce trend distortions and align with real-term dynamics.

To ensure comparability across heterogeneous measures, component-wise min–max scaling is applied within each block with monotonicity preserved. The vector of normalized features z_t is used to construct the block indices and the integral indicator. This scaling delivers an interpretable [0,1] support, maintains the higher-is-better or lower-is-better direction, and avoids overshooting variables with large natural ranges. Blocks are treated as formative constructs; therefore, rather than a reflective measurement model, the simple unweighted mean across block indicators is used. Additionally, robust trend estimators are employed to mitigate the influence of residual outliers.

Methodologically, highlighting X10–X12 within the digitalization block strengthens the link between HC accumulation and technology adoption. Internet penetration, mobile density, and ICT export intensity together capture household access, infrastructure readiness, and external market integration, which are critical for digital technology diffusion and skills monetization in a small open economy.

2.2 Construction of block indices and integral HCSI

For each thematic block b with indicator set I_b the average normalized score is as follows:

$$B_{b,t} = \frac{1}{|I_b|} \sum_{i \in I_b} z_{it}, \tag{1}$$

and the overall index is the unbiased mean of the six block indices:

$$HCSI_t = \frac{1}{6} \sum_{b=1}^{6} B_{b,t}, \tag{2}$$

Internal consistency within each block is monitored using Cronbach's alpha:

$$\alpha = \frac{k}{k-1} \left(1 - \frac{\sum_{i=1}^{k} \sigma_i^2}{\Sigma} \right), \tag{3}$$

where k is the number of indicators in the block; σ_i^2 is the variance of z_{it}; Σ is the variance of the block's summed score.

2.3 Multivariate Methods and Validation

Block PCA. On the matrix of block indices $B \in \mathbb{R}^{T \times 6}$, we compute the covariance matrix $S = \frac{1}{T-1}(B - \bar{B})(B - \bar{B})^T$. The spectral decomposition $S = V \Lambda V^T$ yields eigenvalues $\Lambda = \mathrm{diag}(\lambda_1, \lambda_2, \ldots)$ and eigenvectors V. The explained variance ratio of component j is$EVR_j = \frac{\lambda_j}{\sum_m \lambda_m}$.

Table 2 Block PCA and clustering metrics

Metric	Value
Explained variance of PC1 (%)	80.525
Explained variance of PC2 (%)	8.107
Cumulative explained variance (%)	88.632
Silhouette index	0.561
Calinski-Harabasz index	70.401
Davies-Bouldin index	0.553

Table 3 shows the orthonormal block loadings on the first two components. PC1 represents an economic–digital axis, indicating that productivity growth and digital adoption dominate system-wide variation by shaping the organizational environment in which HC is utilized, whereas demographic factors exert a structural drag. PC2 reflects education–health differentiation and characterizes the internal composition of social investment rather than its aggregate scale.

Table 3 Loadings on the principal components (orthonormal coefficients)

Block	PC1	PC2
Education	0.223	0.726
Health	0.271	-0.623
Innovation	0.057	-0.149
Digitalization	0.617	0.080
Demographics and Labor	-0.170	-0.212
Economy	0.625	-0.092

In the (PC1-PC2) plane, we apply K-means with $K = 3$, minimizing the following:

$$J = \sum_{k=1}^{K} \sum_{t \in C_k} |y_t - \mu_k|^2, \tag{5}$$

where y_t are year coordinates and μ_k is the centroid of cluster k. Partition validity is evaluated using three standard metrics:

- **Silhouette**:
$$s(t) = \frac{b(t) - a(t)}{\max\{a(t), b(t)\}}, \tag{6}$$
where $a(t)$ is the mean intra-cluster distance and $b(t)$ is the minimum inter-cluster distance.

- **Calinski-Harabasz**:
$$CH = \frac{SS_b/(K-1)}{SS_w/(T-K)}, \tag{7}$$

- **Davies-Bouldin**:
$$DB = \frac{1}{K} \sum_k \frac{S_k + S_k^*}{M_k}, \tag{8}$$

The obtained values indicate the stable separability of trajectories into three regimes, which can be interpreted as successive organizational configurations of the national HC system.

Structural Breaks and Trends for the $HCSI_t$ series we use the pruned exact linear time (PELT) algorithm with a quadratic cost and a radial-basis penalty. Breaks were detected around 2000 and 2014, consistent with the trajectory analysis. Trend slopes are estimated using the Theil-Sen estimator: $\hat{\beta} = \text{median}\{(y_j - y_i)/(t_j - t_i)\}$ where $i < j$ with percentile bootstrap confidence interval. The results indicate that convergence is primarily driven by digitalization and economic performance, while innovation and demographic dynamics act as persistent structural constraints due to weak intermediary institutions and limited innovation diffusion mechanisms (Table 4).

Table 4 Theil–Sen trends by block and HCSI (index points per year)

Index	Slope	Lower 95%	Upper 95%
Education	0.01221	0.00428	0.01869
Health	0.01367	0.00691	0.02244
Innovation	0.00118	-0.00423	0.00789
Digitalization	0.03681	0.03167	0.04087
Demographics and Labor	-0.0088	-0.01342	-0.00217
Economy	0.03668	0.03378	0.03950
HCSI (integral)	0.01537	0.01373	0.01695

Between-cluster differences. Inter-cluster differences were tested using one-way ANOVA and the nonparametric Kruskal–Wallis test:

$$F = \frac{SS_{\text{between}}/(K-1)}{SS_{\text{within}}/(T-K)}, \quad H = \frac{12}{T(T+1)} \sum_{k=1}^{K} \frac{R_k^2}{n_k} - 3(T+1), \tag{9}$$

where R_k is the rank sum in cluster k and n_k its size. Both tests are applied to HCSI and each block.

Causality with the output for the pair $(HCSI_t, GDPpc_t)$ we estimate a linear VAR and perform the following Granger causality tests:

$$H_0 : HCSI \nrightarrow GDPpc, \quad H_0 : GDPpc \nrightarrow HCSI, \tag{10}$$

Table 5 summarizes the obtained p-values.

Table 5 Granger causality: p-values for lags of 1–3

Lag	p(GDPpc → HCSI)	p(HCSI → GDPpc)
1	0.368	0.091
2	0.763	0.037
3	0.870	0.119

3. Results and Discussion

3.1 Phase structure and trajectories in block-PCA space

Figure 1 shows the trajectory of annual observations in the coordinates of the first two principal components, which exhibits stable segmentation into three phases with high explained variance. The first component dominates the variance structure, whereas the second captures a substantially smaller but interpretable share related to social subsystem differentiation, with a cumulative share of 88.63% (Table 2). The first component reflects the economic digital axis, with the largest positive loadings for Economy (0.625) and Digitalization (0.617) and a negative loading for Demography and Labor (−0.170). The second component captures education-health differentiation, with opposite signed loadings for Education (0.726) and Health (−0.623) (Table 3). K-means validation yields a silhouette of 0.561, a Calinski–Harabasz index of 70.401, and a Davies–Bouldin index of 0.553, which confirms good separability (Table 2).

In Figure 1, each yearly point is labeled, connected by a dashed polyline, and colored by phase. The PC1 gradient reflects the acceleration of the economic digital core, whereas vertical shifts along PC2 describe the balance between education and health, simplifying the identification of phase transitions. PC1's dominance indicates that economic performance and digitalization provide the primary contribution to interannual shifts in HCSI by reorganizing production and labor-market matching rather than by expanding HC stocks alone. Resource accumulation and digital infrastructure expansion deliver the largest projection effect along PC1, making it the priority channel for accelerating the integral index.

The trajectory in the two-component plane reveals three distinct phases. Phase I covers the early stage of 2000–2006 cluster 2 (Figure 1). The PC1 coordinates lie between −0.677 and −0.355. PC2 lies between −0.235 and −0.017. During Phase I, the system is characterized by low integral HC and weak digital penetration, consistent with an extensive accumulation regime in which organizational and technological feedback to productivity remains limited. Internal characteristics include the rise of Internet users from 1.3% to 5.6% and mobile density from 0.56 to 42.13 subscriptions per 100 inhabitants. GDP per capita grows from 1,229 to 2,551 constant USD. Education block shifts are moderate. Tertiary enrollment increases from 35.3% to 41.8%. Public education spending stabilizes at 2.1%–2.7% of GDP. The correlation matrix shows strong links between digitalization and education and mobile infrastructure; for example, $\rho(X_{10}, X_2) = 0.870$ and $\rho(X_{10}, X_{12}) = 0.873$, and with the economy $\rho(X_{10}, X_{20}) = 0.834$, indicating joint growth of digital and economic metrics. The accumulation regime is predominantly extensive. The ratio of the increase in GDP per capita to the increase in HCSI over the phase is approximately 10.94 thousand USD per one HCSI point ($\Delta GDPpc \approx 1.322$ thousand USD, $\Delta HCSI \approx 0.121$). This signals low returns per unit of HC under a limited digital base ($X_{10} = 1.3\%$–5.6%) and weak mobile density ($X_{12} = 0.56$–42.13) in Figure 1.

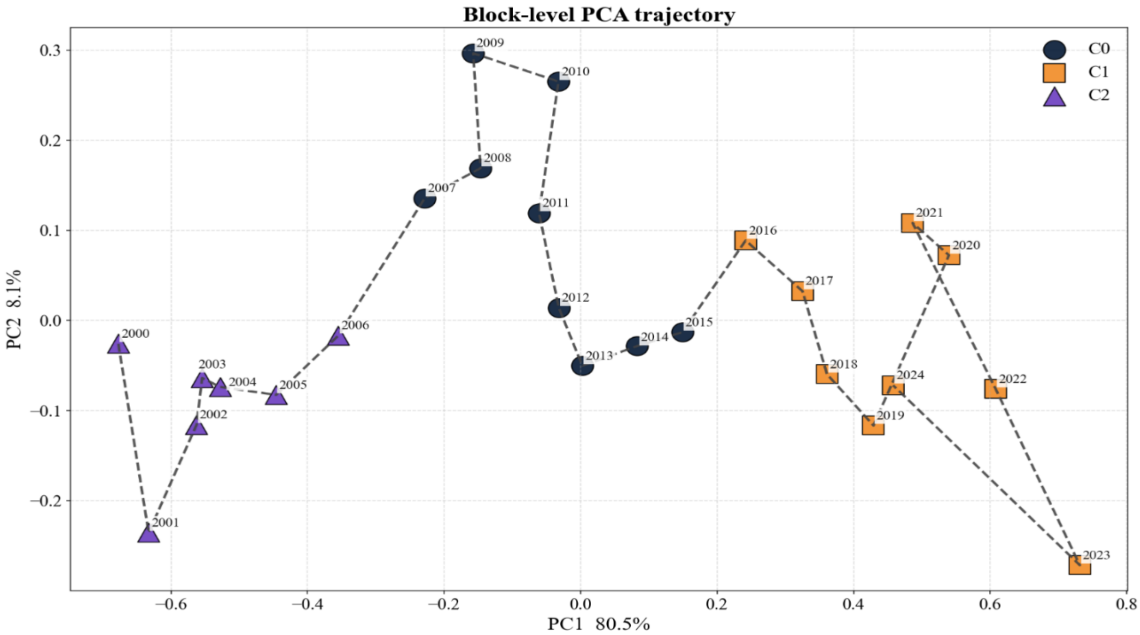

Figure 1 Trajectory in the PCA block space, 2000–2024

Phase II transitional growth includes cluster 0 from 2007 to 2015. The mean HCSI value is 0.439. The shift to positive PC1 values occurs by 2013–2015 (PC1 from 0.003 to 0.149 in 2013–2015). Digitalization accelerates. Internet coverage expands from 6.0% to 59.1%. Mobile density rises from 63.08 to 118.60 per 100 inhabitants. The economy is growing, yet the 2009 crisis produces a sharp drop in GDP per capita from 3,141 to 2,717 USD. Recovery spans from 2010 to 2014 (Figure 3). As predicted by innovation system theory for small open economies, the innovation subsystem remains constrained, preventing digital expansion from being transformed into endogenous technological change due to weak coordination between research, firms, and labor markets. R&D expenditure fluctuates within 0.21%–0.29% of GDP, with a minimum of 0.211% in 2007 and a maximum of 0.291% in 2009. Publication counts increased from 406 to 534 per year. Patent activity is unstable at 116–137 applications. The PELT algorithm detects a change in 2004 (end of the post-crisis recovery in 2004) and another in 2014 (transition to accelerated digital transformation in 2014), which is visible in the HCSI segmentation in Figure 2.

The 2009 crisis generates a deep negative impulse in GDP per capita of –646 USD and shifts the trajectory downward along PC2. After a local peak (PC2 of 0.297 in 2009), PC2 drifts toward the negative zone in 2013–2015 (−0.050, −0.028, −0.013) while PC1 remains stably positive in 2014–2015. With internet coverage still rising from 6.0% to 59.1%, the 2010–2014 recovery relies on digital demand despite stagnant innovation investment (Figures 1 and 3). The average HCSI levels by segment are 0.305 for 2000–2004, 0.420 for 2005–2014, and 0.577 for 2015–2023. The inter-segment jumps are +0.115 and +0.157 points, respectively. This corresponds to a change in the dominant drivers from the basic expansion of education to digitalization and the economy (Figure 2).

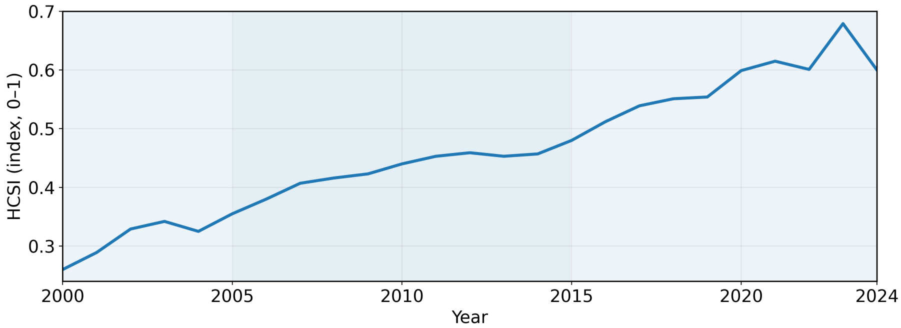

Figure 2 Changes in the HCSI series using three PELT rbf segments: 2000–2004, 2005–2014, and 2015–2023

Phase III new cycle spans cluster 1 from 2016 to 2024. The mean HCSI is 0.589. In 2023, the maximum value is set at 0.679, followed by a moderate correction to 0.600 in 2024. PC1is firmly positive (0.242 to 0.731), consistent with the strong economy and digitalization blocks. Internet coverage will reach 80% by 2023. ICT services exports peaked at 28.86% of services exports in 2020 and then normalized to 18.87% in 2023. Mobile density stabilizes at 120–135 inhabitants per 100 inhabitants. Simultaneously, R&D remain around 0.18%–0.21% of GDP, and youth unemployment remains double digit at 26%–38%, which suppresses the contributions of Innovation, Demography, and Labor to PC1 and PC2. PC2 shifts into the negative territory. In this phase, digital technologies and externally oriented services act as organizational substitutes for a weak domestic innovation system, sustaining growth through reallocative efficiency rather than through cumulative technological learning.

The amplitude of divergences between the normalized series reached 0.11 in 2008 and 0.14 in 2020. In 2009, the divergence was close to 0.006. This is interpreted as a temporary deformation of the HC–output link under external shocks, with the overall trend co-movement preserved (Figure 3).

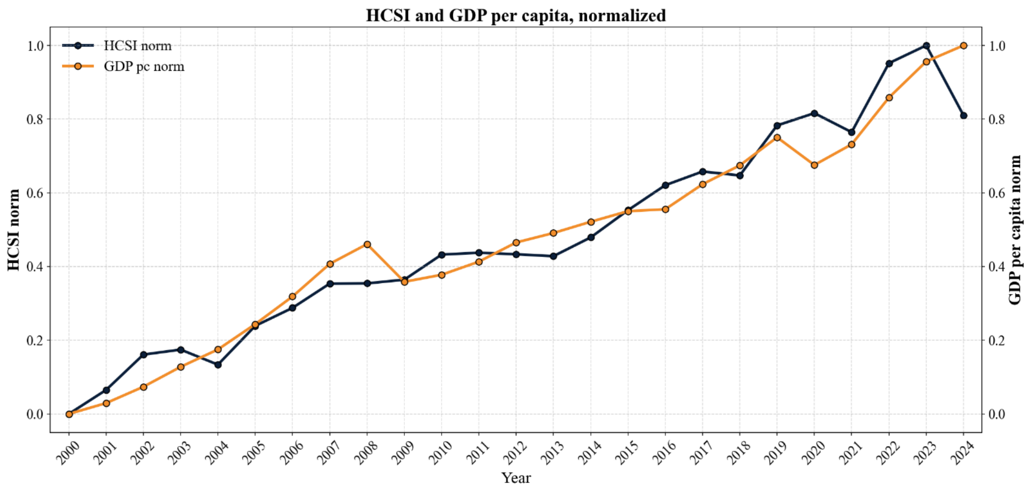

Figure 3 HCSI and GDP per capita with shock markers were normalized

Once the system approaches a critical human-capital threshold, income dynamics shift into an accelerated regime, consistent with nonlinear growth models. In 2019–2023, HCSI remains within 0.59–0.68. The median $\Delta GDPpc$ for 2019–2024 is 274 USD, with an interquartile range of 181–406 USD. Persistently low R&D spending of 0.18%–0.21% of GDP limits transmission into the innovation block. Therefore, contributions to PC1 continue to concentrate on economy and digitalization.

Phase summary. Phase shifts are accompanied by a reduction of interblock heterogeneity in 2012–2014, with a minimum standard deviation across blocks of 0.047–0.065, followed by an increase in 2020–2023 from 0.224 to 0.229. This is interpreted as a non-synchronous acceleration of digitalization and the economy relative to innovation and demographic contours. The PELT identified segments align with the turning points of the trajectory in Figure 1, which supports structural interpretability. The increase in the standard deviation of the blocks from 0.065 in 2014 to 0.229 in 2023 increases the coefficient of variation by roughly 3.5 times. Therefore, the systemic risk of subsystem non-synchrony increases and calls for targeted measures to strengthen innovation, demographics, and labor to smoothen the HCSI trajectory.

3.2 HCSI dynamics and their link to GDP per capita

The integral HCSI rises from 0.260 in 2000 to 0.679 in 2023, followed by a correction to 0.600 in 2024. The mean over 2000–2024 is 0.460, the variance is 0.0135, the standard deviation is 0.116, and the 95% confidence interval for the mean is $[0.412; 0.508]$. The Theil-Sen estimate for the HCSI trend is 0.0154 index points per year with a 95% interval $[0.0137; 0.0170]$, so the decadal increment is close to 0.15 points. The coefficient of variation was 0.252, and the range over the sample was 0.420 points, indicating a large-scale and persistent improvement.

GDP per capita increases from USD 1,229 to USD 5,378 between 2000 and 2024. The average annual growth rate at constant prices is 6.34%. The normalized HCSI and GDP per capita move largely in sync (Figure 3). Exceptions occur in 2009 and 2020 when output falls more rapidly than the human-capital index. The high synchrony between HCSI and income levels indicates that HCS functions as a system-level growth factor embedded in production and organizational structures rather than as an auxiliary social variable. The squared correlation equals 0.94, implying that the co-explained interannual variance in levels is essentially complete.

To link HC with short-run changes in output, we use the following:

$$\Delta GDP_t = GDP_t - GDP_{t-1}, \tag{11}$$

and the linear regression:

$$\Delta GDP_t = \alpha + \beta \cdot HCSI_t + \varepsilon_t, \tag{12}$$

Estimated on 2001–2024, β is approximately 260 USD per HCSI unit. Approximately 26 USD of additional year-over-year growth for a 0.10 point increase in HCSI (Figure 4). The coefficient is positive, with moderate statistical significance at the annual horizon due to high volatility ($p \approx 0.50$). The slope on the phase diagram is small. The Huber M estimation keeps β within 240 to 280 USD, so the sign is invariant.

Causality is assessed using the Granger test in a bivariate VAR. Results show a statistically significant direction of HCSI to GDP at a two-year lag ($p = 0.037$). Hypothesis GDP to HCSI is not rejected ($p = 0.368$, 0.763, and 0.870 for lags 1–3) (Table 5). Interpretation. A delayed payoff from investments in education, health, and digital skills to productivity and income reflects organizational adjustment costs and learning effects emphasized in evolutionary and institutional growth theories. This lag is consistent with the inertia of education and digital projects and the time required for labor-market adjustment.

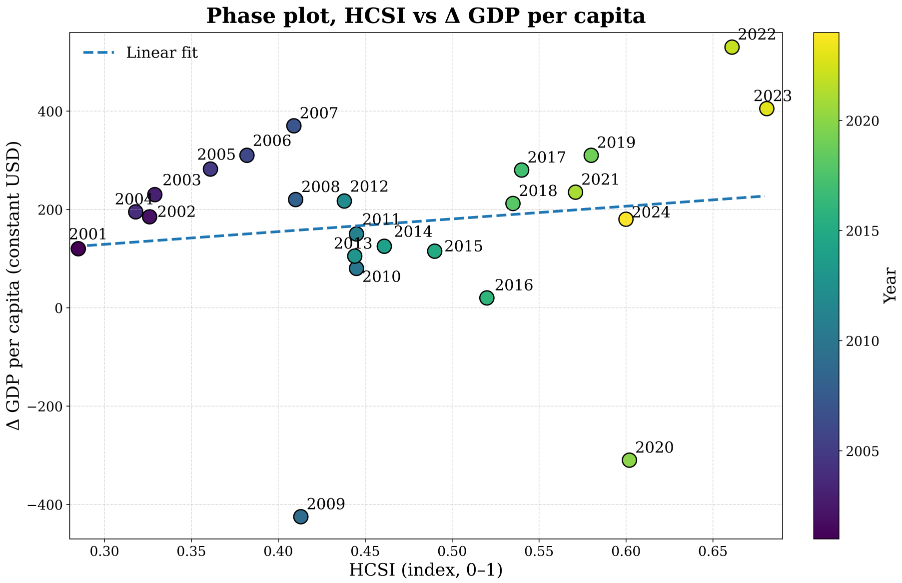

Figure 4 Phase diagram HCSI versus ΔGDP per capita. The slope is positive but moderate. The extremes are the 2009 contraction and the 2022 acceleration

Table 6 aggregates the descriptive statistics for HCSI from 2000 to 2024. The sample size, range, and coefficient of variation are also reported to ease comparison with other subsystem indices. The table reflects the basic distributional moments of HCSI, dispersion, the uncertainty band for the mean, and the robust upward trend. These magnitudes are consistent with Figures 3–5 and support the phase interpretation.

Table 6 Descriptive statistics and reliability parameters of HCSI, 2000–2024.

Indicator	Value	Comment
Number of observations T	25	Years 2000–2024
Mean	0.460	Center of the index distribution
Variance	0.0135	Interannual variability
Standard deviation	0.116	Average amplitude of fluctuations
Minimum	0.260	Year 2000
Maximum	0.679	Year 2023
Range	0.420	0.679 − 0.260
95 percent CI for the mean	$[0.412; 0.508]$	Normal approximation
Coefficient of variation	0.252	$CV = 0.116/0.460$
Theil-Sen trend slope	0.0154 points per year	95 percent CI $[0.0137; 0.0170]$

Finally, the integral trajectory HCSI to GDP (Figure 5) highlights a stepwise ascent. Crossing HCSI approximately 0.60 coincides with the USD 4,500–5,500 band for GDP per capita. The 2020–2021 loop reflects a temporary wedge between HC quality and incomes under an external shock. The segment with an HCSI of at least 0.65 is associated with GDP per capita gains above 400 USD per year from 2022 to 2023, which signals a transition to an accelerated growth regime.

The empirical HC to output link exhibits very high synchronicity in levels ($q = 0.97$) and statistically significant causality with a two-year lag. Surpassing the HCSI threshold of approximately 0.60 is associated with movement to a higher GDP per capita path. This effect's robustness strengthens on segments with faster digitalization and a stable macroenvironment.

3.3 Year clusters, within-cluster differences, and acceleration points

Figure 1 shows the three clusters split by coordinates in the block PCA space. Centers lie at negative PC1 values in the early years and at persistently positive PC1 values in the new cycle. The final ranges and summary metrics are presented in Table 7. Cluster 2 for 2000–2006 features negative PC1 and PC2, a low HCSI level, and comparatively low GDP per capita. Cluster 0 for 2007–2015 shows near zero to moderately positive PC1, with the mean HCSI higher by 0.116 points relative to Cluster 2 and visibly higher incomes. Cluster 1 for 2016–2024 exhibits firmly positive PC1, peak HCSI values, and the highest constant price incomes. One-way ANOVA for HCSI and for the blocks Economy, Digitalization, Education, and Health rejects equality of means at the 5% level. The results for innovation, demographics, and labor are less stable because of the high within-group dispersion. To describe the within-cluster geometry, we also report the means and standard deviations of PC1 and PC2.

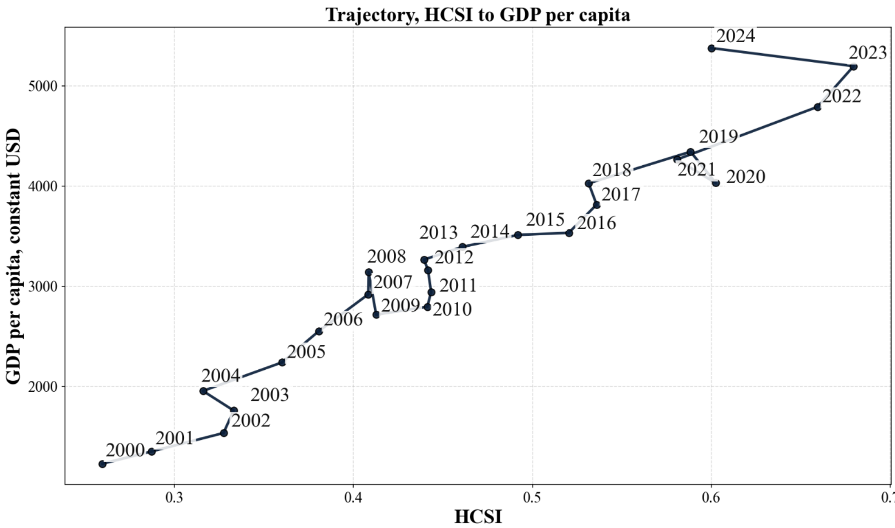

Figure 5 Trajectory "HCSI → GDP per capita," 2000–2024. A gradual rise with local breaks in 2008–2010 and 2020–2021

Table 7 Phase grouping K means and coordinates by components, HCSI, and incomes.

Cluster	Period, years	PC1 range	PC2 range	HCSI, mean	HCSI, median	HCSI, Q1–Q3	GDP per capita, mean, USD
2	2000–2006	-0.677 to -0.355	-0.235 to -0.017	0.323	0.327	0.302–0.347	1,803
0	2007–2015	-0.228 to 0.149	-0.050 to 0.297	0.439	0.441	0.413–0.443	3,094
1	2016–2024	0.242 to 0.731	-0.271 to 0.109	0.589	0.588	0.536–0.602	4,376

Notes: SD denotes the standard deviation. Q1 to Q3 denotes the interquartile range. The PC coordinates follow the year-by-year table. The visual inspection shown in Figure 1 confirms the cluster boundaries.

The within-cluster profile is consistent with that shown in Figure 1. Negative loads from the Demography and Labor block on PC1 dominate in Cluster 2 under weak digitalization, which keeps the trajectory in the lower left quadrant. In Cluster 0, rising digitalization and gradual economic improvement lift PC1 toward zero and then into positive territory, while PC2 is moderately positive and reflects the balance between education and health. Positive Economy and Digitalization loads in Cluster 1 produce a steady rightward shift along PC1, whereas PC2 is mildly negative because Innovation remains weak and labor market pressures persist.

Analysis of the second difference in output highlights the acceleration and deceleration nodes. Acceleration peaks occur at entry into Cluster 1 and in episodes when HCSI exceeds the threshold range, indicating a regime shift in which HCI begins to generate nonlinear productivity effects. This aligns with the phase diagram in Figure 4 and the trajectory in Figure 5. Based on the smoothed second difference, the most pronounced slowdowns fall on phase boundaries and on external shock years, including 2009 and 2024. The numerical estimates are reported in Table 8.

Table 8 Acceleration and deceleration points of the output by the three-year smoothing of the second difference.

Year	2001	2002	2007	2016	2017	2023
Acceleration (Estimate)	0.027	0.034	0.031	0.027	0.025	0.026
Year	2004	2009	2012	2013	2014	2024
Deceleration (Estimate)	0.0096	0.0107	0.0097	-0.0006	0.0058	0.0064

The interpretation of these nodes is consistent with that shown in Figures 3 and 4. Accelerations in 2007, 2016, 2017, and 2023 appear on the phase diagram as shifts toward the upper part of the point cloud when the HCSI is above 0.55. This indicates a threshold regime in which digital technologies and economic reallocation enable organizational consolidation, allowing the conversion of HC into sustained income gains. The slowdowns in 2004, 2009, and 2024 reflect external shocks and transitions between phases that temporarily weaken the link between the HC level and year-over-year output growth.

Methodological takeaway. The mapping from phase to cluster to output acceleration strengthens once the HCSI reaches the thresholds of 0.55–0.60. Therefore, the priority policy includes raising digital inclusion and broadband quality, improving the efficiency of the economy block through the diffusion of productivity-enhancing digital technologies, and reducing within-cluster dispersion in innovation and in demographics and labor to smoothen the HCSI trajectory.

3.4 Discussion

The results support the validity of a block formative approach to measuring HC. Low Cronbach's alpha in Education (0.426), Health (0.054), Innovation (0.054), and Demography and Labor (near zero) reflects the heterogeneous nature of indicators within blocks and justifies unweighted aggregation, whereas Digitalization shows comparatively better internal coherence ($\alpha = 0.665$). This aligns with the long-run logic of HC theory (Becker, 1993; Schultz, 1961) and regional evidence, where education and investment consistently support growth, whereas institutional quality shows mixed effects (Tleppayev et al., 2025). The principal component structure interprets PC1 as an economic–digital axis, consistent with theories of technology-enabled development in which digital infrastructures act as coordination mechanisms rather than isolated inputs and HC as a systemic resource for productivity and convergence (Kulzhanova et al., 2019; Vinokurov, 2017).

Theil-Sen trends capture outperformance in Digitalization by about 0.0368 index points per year and Economy by about 0.0367, moderate gains in Health by about 0.0137 and Education by about 0.0122, stagnation in Innovation by about 0.0012, and a negative slope in Demography and Labor (about -0.0089). High correlations between digital and educational metrics and income indicate a transmission role of digital skills and infrastructure mediated by firm-level reorganization and skill–task matching (Vovchenko et al., 2022). Firm-level evidence supports the micro-mechanism. Knowledge-based HRM practices build intellectual capital and innovation performance (Kianto et al., 2017), and in Industry 4.0 settings, optimal human intellect and AI configurations enhance productivity (Popkova and Sergi, 2020). For Armenia, the digital divide matters. Distance from Yerevan and household income are significantly associated with DTUI and ICT use (Arion et al., 2024), which helps explain the asynchrony of the 2020–2023 block.

Demographic constraints and migration remain the key bottlenecks that weaken domestic skills reproduction and reduce returns to education within national production systems. Shrinking working-age cohorts and brain drain reduce returns to education (Pinxten et al., 2022), while institutional fluctuations and the information environment amplify migration impulses (A. Zaitsev et al., 2023; Yurova, 2023; Vasilyan, 2016). After 2015, the difference in estimates shows that the incomes of migrant-sending households rose by 6%–11% and the gap with non-migrant households narrowed (Oksinenko, 2023). This is accompanied by underutilization of skills at home (Andronova and Ryazantsev, 2023). Policy effectiveness increases when active labor market programs are paired with career guidance (Robertson and Melkumyan, 2021), pronatalist and reintegration measures, and institutional strengthening in education and health (Gagarina et al., 2024; Kuznetsova and Osipova, 2021).

A coordination framework is derived from the sectoral and institutional asymmetries that shape HC monetization. Differences in trade specialization and institutional effectiveness sustain cross-country gaps (Kot et al., 2023; Korosteleva and Petrova, 2021). For small economies, the sustainable monetization of competencies is constrained by non-tariff barriers in services (Hakhverdyan et al., 2025) and by low R&D effort under environmental and fiscal constraints (Zheng et al., 2024; Demidova et al., 2021). In response, mutually recognized qualification standards, co-funded applied R&D, and pilots of digital service platforms are warranted. These measures can leverage clustering and PCA toolkits already proven in agri-food systems and adjacent domains (Rodionov et al., 2025b; Ghazaryan and Aleksanyan, 2024). Sectoral digitalization and intellectual capital cases (Dmitriev et al., 2025; Aleksanyan and Khachatryan, 2024) and approaches to resource rent regulation (A. A. Zaitsev et al., 2024) reinforce practice. Despite power asymmetries, smaller actors can exercise policy agency through negotiated exemptions and agenda setting (Davtyan, 2023), which creates a window for coordinating HC as a shared development priority (Ter-Matevosyan et al., 2017; Vinokurov, 2017).

The comparative indicator panels show a persistent two-cluster structure across the study region. For the Human Capital Index 2020, the five-country mean is approximately 0.638 with a range of 0.12. Belarus (0.70) and Russia (0.68), followed by Kazakhstan (0.63), Kyrgyzstan (0.60), and Armenia (0.58). For the Human Development Index 2023, the mean value is approximately 0.805 with a range of 0.117, from 0.720 in Kyrgyzstan to 0.837 in Kazakhstan. The HDI ranking only partly overlaps with HCI, since Kazakhstan tops HDI and only third in HCI, highlighting differences between development stocks and cohort potential in the HCI logic. Four countries are available for the Network Readiness Index 2024. The mean is about 49.99 points with a range of about 11.6, from 55.74 in Russia to 44.16 in Kyrgyzstan. Armenia and Kazakhstan occupy mid positions at 49.54 and 50.52, respectively. For the Global Knowledge Index 2023, the mean is approximately 47.06 with a range of 6.90. Belarus (51.00) and Russia (47.90) lie above the mean, Armenia (46.71) is close to it, and Kazakhstan (45.60) and Kyrgyzstan (44.10) are below. Intragroup ranking indicates a high ordinal association of HCI with digital readiness (Spearman's correlation 0.8) on the NRI subset and a moderate association with HDI (0.5). This supports the interpretation of PC1 as the economic digital axis and underscores digitalization as a channel that converts HC into income.

Sectoral and institutional gaps reinforce asymmetry. The two R&D tiers stand out. Russia is about 1% of GDP and Belarus about 0.6%, versus about 0.2% in Kazakhstan and Armenia, with Kyrgyzstan still lower. This aligns with weaker GII and NRI positions and constrains the transformation of HC into innovation outputs. Armenia is an atypical case of digital specialization without large-scale R&D. At the 2020 peak, 28.86% of service exports were ICT, while domestic R&D outlays were approximately 0.18%–0.21% of GDP. Thus, the model leans on knowledge export and cross-border services with a limited domestic research base. For convergence corridors, closing HCI gaps without institutional and innovation alignment leads to asymmetric integration into global markets. Migration and dependence on external demand intensify, as evidenced by the effects of household income on migrants (Oksinenko, 2023) and by the interpretation of migration within a social investment model (Andronova and Ryazantsev, 2023). Prioritizing mutually recognized qualification standards and co-funded research and development (R&D) portfolios, linked to digital service platforms, remains key to narrowing gaps and shifting toward an innovation inclusive growth model.

Recent evidence refines how digital technologies convert HC into growth: a Digital Employee Experience framework—spanning tools, workflows, and culture—acts as the "last mile" that translates skills into firm productivity (Moganadas and Goh, 2022); ecosystem levers for IR 4.0—incubation, standards, testbeds, and coordinated upskilling—accelerate the diffusion of innovation capabilities (Surjandari et al., 2022); and platformization plus interoperable data infrastructures expand economy-wide capacity (Berawi, 2022). Country-specific diagnostics further show uneven digitalization across Armenia's government, business, and society (Ayvazyan, 2025), which aligns with our observed blockwise asynchrony (2020–2023) and explains why the HCSI→GDP transmission strengthens only after the ∼0.60 threshold. Policy should therefore target the full pipeline—inclusive broadband/mobile access, DEE-anchored organizational change and SME capability (cloud/AI, data governance, cybersecurity), IR 4.0 testbeds and standards, and performance-based co-funding of applied R&D—to lift the lagging innovation block, rebalance PC2, and make Armenia's digital gains durably translate into higher productivity and export diversification.

By integrating skills, organizational routines, and market access into a coherent productivity-enhancing system, digital technologies form the practical lever for the next stage. Broadband penetration, mobile density, cloud adoption by firms, and ICT-backed professional services' export intensity jointly determine the transmission from skills to incomes. The policy should target friction points along this pipeline. First, inclusion should be increased through last mile connectivity and affordable access in rural areas to address the documented digital divide (Arion et al., 2024). Second, firms' absorptive capacity should be improved through reskilling, modular micro credentials, and incentives for data use, cybersecurity, and AI adoption in small and medium enterprises. Third, anchor demand via innovation-oriented public procurement and interoperable data standards that reduce transaction costs for DSD. Fourth, co-fund applied R&D with performance-based milestones to deepen the innovation block and rebalance the PC2 profile. Together, these measures reduce blockwise asynchrony, increase the return on education and health investments, and stabilize the Human Capital Sustainability Index's upward trajectory.

3.5 Integrated Synthesis of Results and Key Interrelationships

To summarize the empirical findings and the relationships between them, the section includes an integrated overview figure that visually synthesizes the dynamics of HC and economic growth in Armenia from 2000 to 2024. The composite HCS index increases from 0.260 in 2000 to 0.679 in 2023, followed by a correction to 0.600 in 2024, while GDP per capita in constant prices rises from USD 1,229 to USD 5,378. The co-movement of the indicators remains high, with a correlation coefficient of 0.97, whereas short-term divergences are concentrated in years of external shocks, most notably in 2009 and 2020. The development trajectory exhibits a three-phase structure consistent with the results of multivariate diagnostics. In the block-based PCA space, the first PC explains 80.525% of the total variance and reflects the economic-digital axis, with the highest loadings associated with the Economy and Digitalization blocks. The second principal component explains 8.107% of variance and captures the differentiation between education and health social subsystems. K-means clustering in the PC1–PC2 plane yields a stable partition of years into the 2000–2006, 2007–2015, and 2016–2024 periods (Figure 6).

A threshold regime is identified at the macroeconomic response level. Acceleration ofincome growth is observed as HCSI approaches the 0.55–0.60 interval. The Grangercausality test indicates a directional effect from HCSI to GDP per capita with a two-year lag($p = 0.037$). Structural analysis reveals the dominance of digitalization and the economicblock in shaping

HCSI dynamics through organizational and technological mediation, alongside constraining effects from weak innovation intermediation and demographic andlabor-market processes.

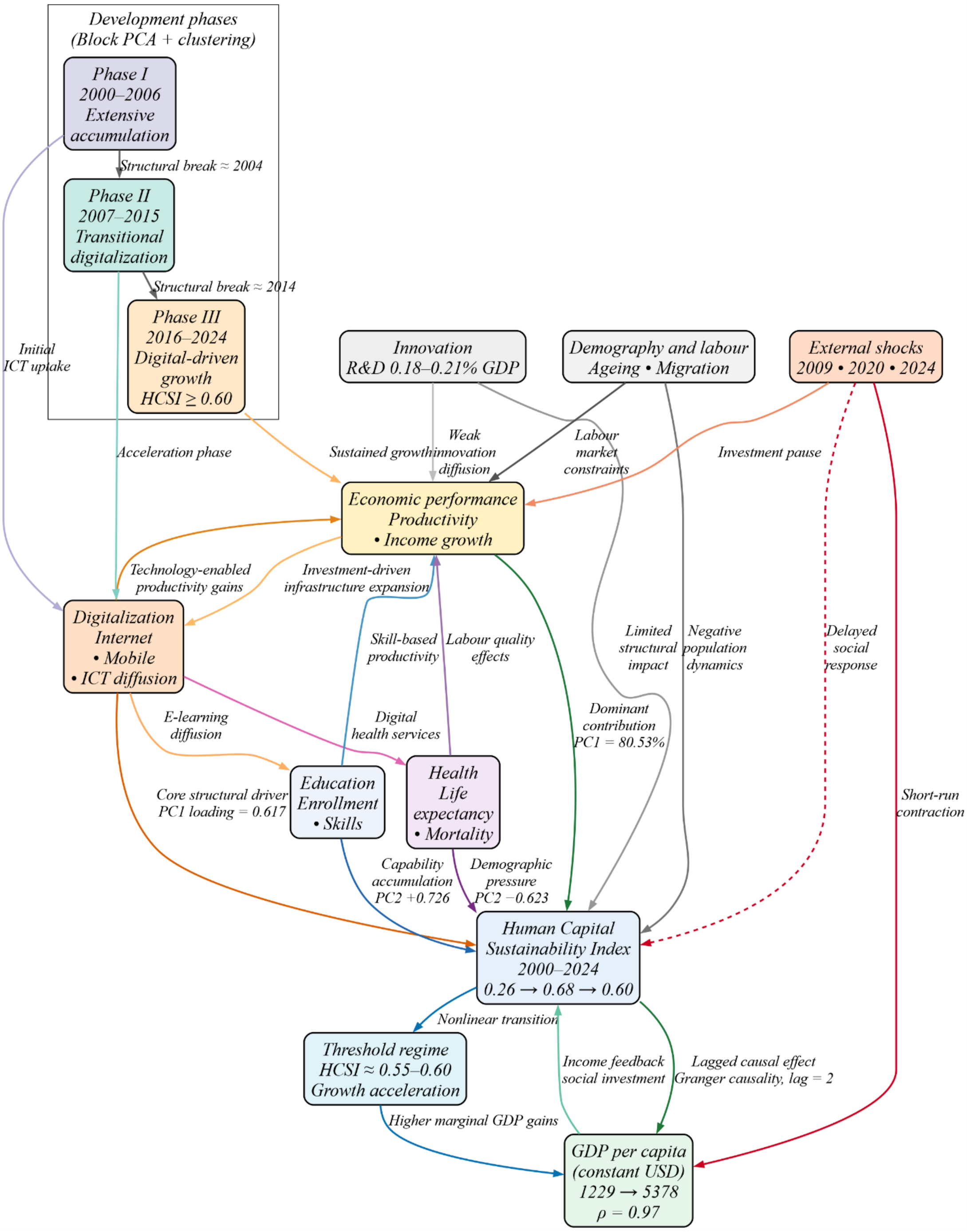

Figure 6 Integrated framework of HC sustainability, digitalization, and economic growth in Armenia (2000–2024)

4. Conclusions

The findings document the sustained accumulation of Armenia's HC and confirm its macroeconomic relevance for socioeconomic consolidation, as evidenced by the long-term upward trajectory of the composite HCSI, its three-phase structure in the block-PCA space, high synchrony with GDP per capita, and a statistically significant causal direction from HCSI to income with a two-year lag. The dominance of the economic–digital axis in the first principal component, combined with a moderate education–health counter-phase in the second component, enables a transparent interpretation of cross-block shifts and reveals a threshold growth regime in which year-over-year income gains strengthen once HCSI approaches approximately 0.60. Digitalization operates as the main transmission channel through broadband access, mobile density, cloud connectivity, and ICT service exports, while risks arise from cross-block asynchrony that intensified during 2020–2023, reflecting innovation inertia and labor-market tensions that dampen multipliers and constrain contributions outside the economic–digital core. Policy implications therefore focus on reducing dispersion across blocks while sustaining digital expansion, including scaling digital skills and infrastructure, adopting mutually recognized qualification standards, co-funding applied R&D and firm-level research collaboration, lowering mobility barriers for skilled labor, and developing interoperable digital platforms for service delivery with shared skills data, complemented by targeted youth employment measures, innovation-oriented public procurement, cybersecurity and data-governance readiness for SMEs, and an export strategy for ICT and ICT-intensive professional services. At the system level, HC should be treated as a common public good, supported by national convergence corridors for HCSI that activate co-financing of upskilling and applied R&D, a unified qualifications framework linking education and industry, expanded internships and dual training, and a shared labor-market and skills data backbone with regular nowcasting to enhance policy responsiveness and reduce structural unemployment, alongside competitive funds for applied research and pilots of digital service platforms with indicative performance targets. The limitations of this study are formative aggregation with low internal consistency in selected blocks, annual data frequency, and potential endogeneity of digitalization. Future research should extend the framework through panel analyses with spatial interdependence, nonlinear and threshold models, causal identification using instrumental variables and difference-in-differences, micro-level validation on household and firm data, and stress testing of sustainability scenarios with real-time nowcasting to strengthen the evidence base for coordinated human-capital- and technology-led growth.

Acknowledgements

This work was supported by the Higher Education and Science Committee of RA (Research project No. $24RL-5B018$ "The Problems and Solutions to Human Capital Management in the Republic of Armenia").

Conflict of Interest

The authors have no conflicts of interest to declare.

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