














“Digital capacity, startup ecosystems, and collaborative governance as drivers of regional economic growth: Evidence from Ukrainian regions”

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ARTICLE INFO	Fedir Zhuravka, Taliat Bielialov, Mykola Sylenko, Dmytro Svyntarenko, Viktoriiia Sliusarenko, Natalia Nebaba and Amet Liumanov (2025). Digital capacity, startup ecosystems, and collaborative governance as drivers of regional economic growth: Evidence from Ukrainian regions. <i>Problems and Perspectives in Management</i> , 23(4), 635-649. doi: 10.21511/ppm.23(4).2025.43
DOI	http://dx.doi.org/10.21511/ppm.23(4).2025.43
RELEASED ON	Tuesday, 23 December 2025
RECEIVED ON	Tuesday, 28 October 2025
ACCEPTED ON	Friday, 19 December 2025
LICENSE	 This work is licensed under a Creative Commons Attribution 4.0 International License
JOURNAL	"Problems and Perspectives in Management"
ISSN PRINT	1727-7051
ISSN ONLINE	1810-5467
PUBLISHER	LLC “Consulting Publishing Company “Business Perspectives”
FOUNDER	LLC “Consulting Publishing Company “Business Perspectives”



NUMBER OF REFERENCES

52



NUMBER OF FIGURES

0



NUMBER OF TABLES

5

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BUSINESS PERSPECTIVES



LLC "CPC "Business Perspectives"
Hryhorii Skovoroda lane, 10,
Sumy, 40022, Ukraine
www.businessperspectives.org

Type of the article: Research Article

Received on: 28th of October, 2025

Accepted on: 19th of December, 2025

Published on: 23rd of December, 2025

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Conflict of interest statement:

Author(s) reported no conflict of interest

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DIGITAL CAPACITY, STARTUP ECOSYSTEMS, AND COLLABORATIVE GOVERNANCE AS DRIVERS OF REGIONAL ECONOMIC GROWTH: EVIDENCE FROM UKRAINIAN REGIONS

Abstract

This study develops and empirically tests a composite framework for assessing the digital and innovation capacity of Ukrainian regions. The aim is to evaluate the impact of digital innovation capacity on regional economic performance under conditions of systemic disruption with the Virtual Growth Poles Index (VGPI) which captures four dimensions using observable indicators: 1) digital infrastructure readiness, 2) mobile internet coverage and uptake of digital public services, 3) startup ecosystem activity, and 4) governance and civic collaboration, which reflects participatory budgeting intensity, use of civic tech platforms, and open-data engagement.

Using a panel dataset of 24 Ukrainian regions for 2018–2024, we apply correlation analysis and fixed-effects regression models to quantify the contribution of digital and innovation capacity to regional economic performance. The VGPI shows a moderate yet stable correlation with per capita GRP growth ($r \approx 0.50$). Regression estimates show that a 0.1 increase in VGPI is associated with an additional 0.07–0.09 percentage point increase in regional GRP growth, controlling for unemployment, industrial structure, and war exposure. Most substantial effects are observed in regions with high digital readiness and collaborative governance (Kyiv City, Lviv and Dnipropetrovsk regions), while war-affected regions (Sumy, Chernihiv, Zaporizhzhia, and Kherson regions) show substantially lower VGPI values and weaker economic performance. These findings suggest that in conditions of severe structural disruption caused by Russia's war against Ukraine, strengthened digital ecosystems and collaborative governance structures can partially compensate for damaged physical infrastructure and enhance regional resilience.

Keywords

virtual growth poles, strategy, digitalization, startup ecosystems, governance, regional development

JEL Classification

R11, O33, H72, L26

INTRODUCTION

The rapid digital transformation of economies is reshaping traditional approaches to regional and municipal development. The increasing role of digital infrastructure, platform-based governance, and innovation ecosystems has changed the mechanisms through which territories generate economic value and public services. For countries undergoing systemic disruption, these transformations become especially critical. In Ukraine, the full-scale Russian invasion and ongoing war against Ukraine have caused extensive damage to physical infrastructure, disrupted territorial economic systems, and deepened regional inequalities. At the same time, the continuity of digital public services, the expansion of civic technologies, and the resilience of the IT sec-

tor have revealed the growing importance of virtual and network-based development mechanisms for maintaining regional functionality and economic activity. Human capital also plays a critical role in shaping the capacity of regions to engage in digital transformation and innovation-driven development. Regions with stronger educational attainment levels tend to adopt digital technologies more rapidly, develop more dynamic startup ecosystems, and participate more actively in collaborative governance mechanisms. Given these linkages, regional differences in education must be considered when analyzing the drivers of economic growth.

Although classical models of regional development, such as growth poles, territorial clusters, and innovation systems, remain relevant, they largely rely on physical proximity and spatial concentration. In contrast, contemporary development processes increasingly depend on digital platforms, remote interaction, and distributed networks that transcend geographic boundaries. This shift creates a need for new frameworks that integrate digitalization, public governance, and regional development. However, existing studies on digital public infrastructure, startup ecosystems, and collaborative governance tend to consider these elements separately, without linking them into a unified and measurable regional development model.

1. LITERATURE REVIEW

The literature on regional development has increasingly emphasized the role of digital transformation, entrepreneurial ecosystems, and collaborative governance as key determinants of territorial economic performance. Existing research spans several domains, including digitalization and regional competitiveness, startup ecosystem dynamics, public governance and civic participation, and innovation-oriented public finance. Although these strands have mainly developed in parallel, they collectively highlight the growing importance of non-material and network-based factors in shaping regional growth trajectories.

1.1. Regional development and public-municipal finance perspective

Contemporary regional development literature increasingly frames digitalization as both a spatial and institutional transformation, rather than merely a technological upgrade of existing infrastructures. Nordic studies show that digital tools can support sustainable regional development by improving public service efficiency, enabling cross-municipal cooperation, and strengthening citizen participation in peripheral areas (Randall, 2018). Similar results are found in Central and Eastern European contexts, where the quality of the information and communication environment shapes how

regions can harness digitalization to unlock the potential of all territories and reduce intra-regional disparities (Kondratenko et al., 2022; D'yakonova et al., 2018).

From the perspective of public and municipal finance, digital transformation is not neutral: it alters revenue structures, expenditure priorities, and governance architectures. Empirical research on Chinese provinces shows that local public service delivery is a key driver of regional digital transformation, with local governments acting as central orchestrators of digital ecosystems that link public services, market development, and higher education institutions (Pu et al., 2025). In European regions, e-governance and digital public management are analyzed as crucial components of regional development policy, shifting the emphasis from the national to the inter-municipal and regional levels and prompting the redesign of management mechanisms and budgetary processes (Gazuda, 2025).

Regional digitalization strategies must be embedded in broader development and industrial policies. Studies on regional industrial digitalization highlight the risk of “lock-in” when policy focuses narrowly on existing sectors and argue for asset modification and new policy mixes that integrate digital tools into regional restructuring strategies (Isaksen & Rypestøl, 2022). In parallel, research on regional entrepreneurial ecosystems demonstrates the need for evidence-based policy frame-

works tailored to local conditions, emphasizing that financial and regulatory instruments must be aligned with ecosystem bottlenecks and opportunities (von Bloh, 2021; OECD, 2023).

Overall, the regional development and public-finance literature converges on three ideas that are central for virtual growth poles:

1. Digitalization has a strong territorial dimension.
2. Local and regional governments play an active role as investors, regulators, and platform builders.
3. Regional entrepreneurial ecosystems require dedicated, place-sensitive financial instruments embedded in public–municipal finance systems.

1.2. Startup ecosystems, digital innovation, and virtual clusters

The notion of entrepreneurial or startup ecosystems has evolved into a central framework for understanding innovation-driven regional development. Foundational reviews conceptualize entrepreneurial ecosystems as place-based configurations of interdependent actors, institutions, and cultural attributes that collectively support productive entrepreneurship (Malecki, 2018). Building on earlier ecosystem models (e.g., Isenberg, 2016), ecosystem health depends on the dynamic alignment of policy, finance, talent, markets, and culture, warning against simplistic “copy-Silicon-Valley” strategies.

Newer research directions explore how entrepreneurial ecosystems are shaped by public policy and, in turn, how they inform regional strategies. Hess et al. (2025) argue that future ecosystem research must better integrate public policy perspectives, including issues of inclusion, sustainability, and long-term institutional learning. In different country contexts, regional entrepreneurial ecosystems influence entrepreneurial development, but their effectiveness depends on enabling institutions, access to finance, and knowledge exchange networks (von Bloh, 2021; Oliynyk et al., 2017; Audretsch et al., 2025; OECD, 2023).

A growing body of literature emphasizes that education systems (notably higher education institutions and vocational training structures) are foundational elements of regional innovation capacity. Educational attainment increases absorptive capacity, supports the formation of digital skills, and enhances the ability of firms and local institutions to engage in collaborative governance (Autor et al., 2023; Rodriguez-Pose, 1994). Regions with stronger human capital bases exhibit more dynamic startup formation and higher diffusion of digital public services, suggesting that education moderates the effectiveness of digital and innovation-oriented development strategies.

Digitalization adds a further layer by transforming the spatial and organizational logic of ecosystems. Studies on digital finance show that it can enhance regional innovation capacity by improving access to financial services, reducing transaction costs, and facilitating resource allocation to innovative firms and projects (Hui et al., 2023; Dong & Pan, 2024). Research on the digital economy and regional development similarly concludes that higher levels of industrial digitalization are associated with improved regional performance and firm-level outcomes (Huang et al., 2022; Bondarenko et al., 2020).

A related strand examines virtual clusters and digital regions, which directly informs the idea of virtual growth poles. Early work on virtual clusters described them as systems of geographically dispersed but digitally connected actors that jointly create value in specific domains, supported by knowledge hubs and smart community strategies (Passiante et al., 2003). Participation in virtual clusters improves innovation performance, especially for smaller firms with high network centrality and brokerage positions (Kang et al., 2022). Policy documents mapping Internet-of-Things innovation clusters in Europe further distinguish virtual clusters as collaborative, goal-oriented networks where actors are not co-located but linked through digital infrastructures and platforms.

Taken together, these streams suggest that startup ecosystems increasingly operate in hybrid spaces where regional embeddedness and virtual connectivity co-exist. This creates fertile ground for conceptualizing virtual growth poles as digitally

mediated nodes of entrepreneurial and innovative activity, anchored in regional strategies but not constrained by geographical co-location.

1.3. Triple Helix, public-community-business collaboration, and digital participatory finance

The governance of innovation and regional development is often analyzed through the Triple Helix framework, which depicts innovation as the outcome of interactions among universities, industry, and government. Classic contributions by Leydesdorff and Etzkowitz (1998) conceptualize the Triple Helix as an evolving communication overlay on institutional arrangements, generating new hybrid organizations and policy instruments for knowledge-based development. Cai and Lattu (2022) question whether the Triple Helix is sufficient for contemporary policy challenges and propose the Quadruple Helix model, which explicitly adds civil society and the public as a fourth actor, highlighting societal needs and democratic legitimacy.

In parallel, innovation ecosystem studies emphasize that effective regional development increasingly depends on collaborative governance, co-creation, and shared responsibility among public authorities, businesses, universities, and communities (Hess et al., 2025). This aligns with practical experiments in participatory budgeting and digital democratic tools. Participatory budgeting is framed as a democratic innovation in public finance that allows citizens to directly influence the allocation of portions of municipal budgets, thereby linking community development priorities with fiscal decision-making (Schugurensky & Mook, 2024). A recent European Parliament briefing underscores that participatory budgeting is particularly compatible with digital democracy, in which online tools can broaden participation and make budgetary processes more transparent and impact-oriented (European Parliament Research Service, 2024).

Digital participation platforms such as Decidim and CONSUL have been implemented in numerous cities and regions to support participatory budgeting and other participatory processes, enabling large-scale online engagement and inte-

grating citizen input into public financial decisions (Center for Borgerdialog, 2021). Empirical studies on digital participatory budgeting in Scotland show how local governments develop new digital capabilities, adapt internal procedures, and work with community groups to institutionalize participatory processes (Davies et al., 2022; OECD-OPSI, 2023). Similar initiatives in cities such as Yerevan use digital platforms to channel citizen proposals into annual municipal budgets, with dedicated budget lines for selected projects (Open Government Partnership, 2021).

All these strands can be integrated into a public-community-business collaboration model for virtual growth poles. The Triple/Quadruple Helix literature provides the theoretical lens for multi-actor innovation governance; entrepreneurial ecosystem and virtual cluster studies clarify the role of startups and networks; and digital participatory budgeting experiences illustrate how communities can be directly involved in prioritizing and financing innovation and development projects at the municipal level. The role of startup ecosystems as a driver of regional growth aligns with research on venture entrepreneurship and state regulation mechanisms in Ukraine (Tymoshenko et al., 2022), while the digital marketing and mobile-platform dimension reflects recent evidence from smart-economy and app-based innovation studies (Kolesnyk & Kostynets, 2024). Such an integrated perspective opens the way for conceptualizing virtual growth poles as digitally orchestrated helix-based formations, where local governments, businesses, knowledge institutions, and communities co-design strategies, share data, and co-decide on resource allocation within a regional digital space.

1.4. Traditional growth poles and territorial innovation models

The classical concept of growth poles, introduced by Perroux (1950) in the mid-20th century, defined regional development as a spatially concentrated process within dominant industrial centers that generate spread effects across surrounding territories. Growth poles rely on physical agglomeration, industrial concentration, and territorial proximity to stimulate regional spillovers, create economies of scale, and attract investment. Subsequent models, such as industrial districts, technoparks, and

territorial clusters, followed a similar logic: spatial co-location of firms, institutions, and infrastructure is assumed to be the primary driver of innovation and productivity.

The origins of regional development theory emphasize spatial concentration. Perroux's early growth pole theory described development as driven by dominant economic centers that generate spread effects. Later, the literature on industrial clusters and regional innovation systems (e.g., Porter, 1998; Asheim & Gertler, 2005) highlighted the benefits of geographical proximity, including knowledge spillovers, shared labor pools, institutional thickness, and stable networks.

These models shaped regional policy globally, underpinning public investments in industrial zones, science parks, and special economic areas. However, they exhibit several limitations in the context of the contemporary digital economy:

- geographic dependency restricts participation of rural, remote, or crisis-affected regions;
- heavy infrastructure investment requirements limit scalability;
- spatial clustering is vulnerable to shocks (economic crises, geopolitical disruptions, war);
- innovation increasingly occurs in distributed digital networks beyond physical boundaries.

Clusters depend strongly on localized physical infrastructure, making them vulnerable to spatial inequality, economic shocks, or disruptions to physical connectivity. In Ukraine, where many industrial clusters have been severely damaged or displaced due to Russia's full-scale invasion, these limitations are particularly relevant. The traditional territorial logic of clusters struggles to accommodate fragmented geographies, large-scale migration, and intensified digitization of economic activity. Digital transformation has fundamentally altered how innovation ecosystems operate. With high-speed internet, cloud computing, virtual collaboration tools, data platforms, and distributed work models, innovation is no longer tied exclusively to physical co-location.

Over the last two decades, innovation theory has expanded toward concepts such as virtual clusters (Passiante & Secundo, 2002), virtual innovation systems (Asheim & Gertler, 2005), digital innovation hubs (EU policy framework), platform ecosystems (Li et al., 2025), and virtual entrepreneurial ecosystems (Kang et al., 2022).

Passiante and Secundo (2002) conceptualized virtual clusters where "transactions become space independent." Passiante together with Elia and Massari (2003) expanded this perspective, arguing that interconnected firms form virtual innovation systems, in which value creation depends on digital proximity rather than spatial proximity. More recent studies (e.g., Li et al., 2025) show how multi-actor collaborations within platform ecosystems operate across geographical boundaries. Kang et al. (2022) provide empirical evidence of virtual cluster participation improving firms' innovation performance.

These findings (Table 1) imply that regional development must incorporate the logic of digital proximity, platform connectivity, and distributed innovation, particularly in contexts where physical infrastructures are disrupted. Described models shift the focus from geography to digitally mediated network interactions, coordinated through shared data infrastructures, cloud systems, online marketplaces, and collaborative platforms. Governance becomes more horizontal, multi-actor, and participatory, while innovation processes become more modular and distributed.

Digitalization has fundamentally altered the logic of regional development. The proliferation of high-speed connectivity, cloud computing, remote collaboration tools, digital marketplaces, and data platforms has enabled new forms of economic activity that no longer depend on geographic proximity.

This transition is also visible in Ukraine's digital governance reforms (e.g., Diia, open data portals) and in its resilient IT sector, which continues operating remotely despite wartime disruptions. These conditions make virtual ecosystems more relevant than traditional territorial clusters.

Building on the shift from spatial to networked innovation systems, virtual growth poles (VGPs)

Table 1. Literature synthesis

Source	Contribution	Implication for VGPs
Perroux (1950)	Growth poles, territorial economic drivers	VGPs extend beyond territorial logic
Porter (1998)	Cluster competitiveness, spatial proximity	VGPs reinterpret clusters via digital proximity
Asheim and Gertler (2005)	Regional innovation systems	VGPs incorporate multi-actor, institutional dynamics
Passiante and Secundo(2002)	Virtual clusters	Foundational for digitalized innovation spaces
Passiante et al. (2003)	Virtual innovation systems	Evidence for networked, non-spatial innovation
Kang et al. (2022)	Empirical evidence for virtual cluster performance	Supports VGP effectiveness
Li et al. (2025)	Platform ecosystems	Framework for VGP governance
OECD (2024)	Digital resilience of Ukrainian business	Confirms the feasibility of VGPs

are defined as digitally orchestrated, multi-actor regional innovation nodes that integrate startups, businesses, public authorities, research institutions, and communities via shared digital infrastructure, data platforms, and collaborative finance instruments, functioning beyond strict physical co-location.

Key characteristics of VGPs include:

- Non-geographical anchoring – regional innovation nodes extend beyond territorial boundaries.
- Platform-based orchestration – coordination occurs through digital platforms and shared data infrastructures.
- Hybrid proximity – digital proximity complements or substitutes physical proximity.
- Distributed innovation capacity – innovation emerges across networks, not just within local clusters.
- Crisis resilience – digital systems continue operating despite war, occupation, or physical infrastructure loss.
- Integration with public and municipal finance – VGPs utilize local budgets, participatory budgeting tools, innovation grants, startup vouchers, and blended finance.

This framework aligns with Ukraine's wartime and post-war recovery priorities: scalability, cost-efficiency, resilience, and inclusiveness across re-

gions with asymmetric development. Ukraine exhibits four structural conditions that make VGPs not only relevant but necessary, including physical cluster disruption, because, due to war, traditional cluster models are no longer sufficient. Strong digital infrastructure, including advanced e-governance, widespread electronic services, and high digital literacy, geographically dispersed but globally integrated IT and startup ecosystems, and high levels of civic engagement and public-sector digitalization, enabling participatory and data-driven governance. Thus, virtual growth poles offer a framework that bridges regional development, digital transformation, and innovation policy under conditions of crisis, reconstruction, and limited physical infrastructure.

1.5. Ukrainian context: Digital transformation, regional development, and innovation ecosystems

Ukraine presents a compelling case for examining virtual growth poles because of its rapid digitalization trajectory, the war-related acceleration of innovation dynamics, and marked regional disparities in development. Recent research shows that digitalization in Ukraine has become a strategic lever for regional development. Kondratenko (2022) finds that digital infrastructure and services are increasingly decisive for regional resilience and competitiveness. Yuriychuk et al. (2025) identify major trends, including the growth of digital public services, remote access platforms, and regional digital readiness indicators. At the same time, regional disparities continue to hamper development.

Huk and Zeynalov (2022) show that government spending, migration, human capital, and resource endowments explain the widening gaps between Ukraine's regions. Thus, Ukraine combines digital momentum with uneven regional capacities, creating fertile ground for network-based, non-territorial innovation nodes (i.e., virtual growth poles) to reduce spatial inequalities potentially.

Empirical studies of Ukrainian startup ecosystems underscore both high potential and structural challenges. Mazur (2023) ranks regional startup ecosystems in Ukraine and finds that a large share of activity remains concentrated in Kyiv, while other regions underperform on key indicators such as financing, infrastructure, and mentorship. Donets (2025) reports that despite a domestic startup ecosystem valuation of ca. €28 billion, regional imbalances persist and institutional support remains fragmented.

In the wartime context, a 2024 study (Khaustova et al., 2024) notes that political instability and economic disruption have forced the Ukrainian startup ecosystem to adapt via distributed teams, remote investment, and digital accelerator models. These observations emphasize that the Ukrainian case shows both why virtual/decoupled innovation nodes make sense (given spatial and conflict-driven disruption) and why institutional/financial mechanisms must be regionally sensitive.

Ukraine's decentralization reforms since 2014 have shifted more authority and budgetary capacity to local governments, thereby enhancing the role of municipalities in innovation and regional development. Cluster initiatives, municipal innovation programs, and participatory budgeting practices are growing. For example, a 2025 analysis of Ukrainian cluster ecosystems (Hladchuk et al., 2025) highlights the increasing involvement of regional authorities, business networks, and academia in forming innovation alliances. Furthermore, digital participation and civic tech tools are gaining traction in Ukraine's local governance. Although less research is publicly available, several case studies (Gazuda et al., 2025) indicate that community involvement via e-platforms is becoming part of municipal development practice. Thus, the Ukrainian context demonstrates the feasibility of a collaborative model (public–business–

community), which is central to the concept of virtual growth poles.

The convergence of digital readiness, startup dynamism, and institutional reform in Ukraine suggests that creating virtual growth poles could be both timely and strategic. The spatial fragmentation caused by war, migration, and infrastructure damage makes traditional location-bound clusters less feasible; virtual nodes restore connectivity across regions. The strong concentration of startup activity in Kyiv and the lack of balanced regional ecosystems provide a motivation for networked poles that link peripheral regions digitally to global innovation flows. Municipalities with enhanced autonomy and digital platforms can act as orchestrators of virtual poles, connecting local assets with national/international networks.

In short, the Ukrainian experience offers a natural laboratory for studying how virtual growth poles might reduce regional inequality, accelerate startup ecosystems, and leverage public–private–community collaboration under conditions of disruption.

Following the literature review, this study aims to assess the impact of regional digital and innovation capacity on regional economic performance under conditions of systemic disruption.

2. METHODOLOGY

An original model of a virtual growth pole (VGP) is designed to stimulate regional development through digital infrastructures, startup ecosystems, and multi-actor collaboration. The model reflects the shift from territorial to network-based innovation dynamics and aligns with modern principles of public governance, municipal finance, and digital transformation.

A virtual growth pole is defined as a digitally mediated, platform-based, multi-actor innovation node that coordinates startups, public authorities, businesses, research institutions, and communities through shared digital infrastructures, distributed governance mechanisms, and collaborative financing tools to generate regional development outcomes independent of spatial co-location.

The purpose of the VGP model is to strengthen regional innovation capacity, integrate peripheral or crisis-affected territories into national and global innovation networks, enhance municipal governance through digital participation and data-driven tools, provide scalable, low-cost mechanisms for fostering entrepreneurship and investment, and support regional resilience and reconstruction.

The proposed model consists of four interconnected layers, each responsible for specific functions within the regional innovation system (Figure 1).

Layer 1, “Digital Infrastructure Layer,” is a foundational layer that includes the core technological components enabling interaction, coordination, and data exchange. This layer ensures connectivity, transparency, and accessibility across all actors. Layer 2, “Ecosystem Actor Layer (participants),” comprises four actor groups aligned with the Quadruple Helix. Their interaction is mediated digitally through the platform (Layer 1). Layer 3, “Innovation Process Layer,” includes a set of inter-linked processes described in Figure 1. These processes create a continuous innovation flow within the virtual environment. Layer 4, “Governance and Finance Layer,” includes coordination and sustainability to ensure long-term operation of the VGP system. This layer provides institutional stability and financial sustainability. The inclusion of governance and fiscal coordination indicators is consistent with prior evidence on decentralization and budgetary security in Ukraine (Kosova et al., 2021).

The empirical analysis uses a regional panel dataset covering 24 regions of Ukraine for the period 2018–2024. The choice of period reflects the availability of comparable regional indicators for digitalization, innovation activity, public finance, and socio-economic outcomes. The dataset excludes temporarily occupied territories where official statistics have been discontinued. Spatial units are 24 regions (oblasts); time units are 7 years (2018–2024), which means a total of $24 \times 7 = 168$ region-year observations. This balanced panel allows for estimation of fixed effects models and analysis of time trends in virtual growth poles.

The variables are organized into five categories: digital (D), startup ecosystem (S), governance (G), finance (F), and outcome (Y). Table 2 summarizes the variables.

Control variables include population density, industrial structure, unemployment rate, and war intensity proxy (distance to the frontline, 2022–2024).

Table 2 provides the full list of variables used to construct the dataset and analytical framework. The four sub-indices (DII, SEI, GCI, and FII) exhibit substantial interregional variation, which aligns with known differences in digital infrastructure, startup activity, public governance quality, and innovation finance across Ukrainian regions. The composite VGPI demonstrates sufficient dispersion to meaningfully differentiate regional development trajectories.

Table 2. Variables used in the construction of VGPI and regression analysis

Variable	Definition	Source
DII	Digital Infrastructure Index (normalized 0–1, composite of broadband, e-services, cloud adoption, digital public infrastructure)	Ministry of Digital Transformation of Ukraine, EGAP, regional ICT statistics
SEI	Startup Ecosystem Index (normalized 0–1, includes ICT firms per 10,000 population, number of startups, innovation-active firms, ecosystem institutions)	State Statistics Service of Ukraine (Derzhstat), IT Ukraine Association, TechUkraine, Ukrainian Startup Fund
GCI	Governance & Collaboration Index (normalized 0–1, includes participatory budgeting intensity, civic-tech usage, open data activity, e-participation)	OpenData Portal, PB platforms, local e-government reports
FII	Innovation Finance Index (normalized 0–1, includes local budget spending on innovation, digitalization, PPP projects, and grants)	OpenBudget, municipal budget programs, donor project statistics
VGPI	Virtual Growth Pole Index (composite index: $0.25 \cdot \text{DII} + 0.25 \cdot \text{SEI} + 0.25 \cdot \text{GCI} + 0.25 \cdot \text{FII}$)	Our calculations
GRP_growth	Annual growth rate of Gross Regional Product per capita (%)	State Statistics Service of Ukraine (Derzhstat)
Unemployment	Unemployment rate by region (%)	State Statistics Service of Ukraine (Derzhstat)
Industrial_share	Share of manufacturing in regional GRP (%)	State Statistics Service of Ukraine (Derzhstat)
War_exposure	Dummy variable, 1 = high exposure to military conflict, 0 = low	Our coding based on official war damage and frontline maps

All raw indicators x_{it} are normalised using the min–max method:

$$x_{it}^* = \frac{x_{it} - \min(x)}{\max(x) - \min(x)}. \quad (1)$$

For negative-orientation indicators (e.g., share of analog services), the transformation is reversed. For each dimension:

$$DII_{it} = \sum_{k=1}^{K_D} w_k^D D_{kit}^*, \quad SEI_{it} = \sum_{m=1}^{K_S} w_m^S S_{mit}^*, \quad (2)$$

$$GCI_{it} = \sum_{r=1}^{K_G} w_r^G G_{rit}^*, \quad FII_{it} = \sum_{q=1}^{K_F} w_q^F F_{qit}^*. \quad (3)$$

Weights w may be equal (baseline) or derived using PCA/FA. Virtual Growth Pole Index could be counted as:

$$\begin{aligned} VGPI_{it} &= \alpha_D DII_{it} + \alpha_S SEI_{it} \\ &+ \alpha_G GCI_{it} + \alpha_F FII_{it}, \quad (4) \\ \alpha_D + \alpha_S + \alpha_G + \alpha_F &= 1. \end{aligned}$$

Baseline specification uses equal weights $a_D = a_S = a_G = a_F = 0.25$.

Pearson’s correlation coefficient is used to explore bivariate relationships between VGPI and GRP growth:

$$\begin{aligned} \rho_{VGPI,Y} &= \frac{\sum_{i,t} (VGPI_{it} - \overline{VGPI})(Y_{it} - \bar{Y})}{\sqrt{\sum_{i,t} (VGPI_{it} - \overline{VGPI})^2} \sqrt{\sum_{i,t} (Y_{it} - \bar{Y})^2}}. \quad (5) \end{aligned}$$

To identify the impact of virtual growth poles on regional development, we estimate a fixed-effects panel regression:

$$Y_{it} = \beta_0 + \beta_1 VGPI_{it} + \gamma' Z_{it} + \mu_i + \tau_t + \varepsilon_{it}, \quad (6)$$

where Y_{it} – GRP per capita growth; $VGPI_{it}$ – Virtual Growth Pole Index; Z_{it} – vector of controls; μ_i – region fixed effects (eliminate unobserved heterogeneity); τ_t – time fixed effects (account for shocks, including wartime effects post-2022).

A positive, statistically significant β_1 supports the hypothesis that stronger virtual growth poles are associated with improved regional economic performance.

To verify the robustness of the results, we employ:

1. Alternative weighting schemes (PCA-derived weights).
2. Lagged VGPI model to address potential reverse causality:

$$Y_{it} = \beta_0 + \beta_1 VGPI_{i,t-1} + \dots \quad (7)$$

3. Alternative dependent variables (employment growth, investment per capita).
4. Clustered standard errors at the regional level.

The analysis is implemented using Excel for initial index calculation; R (plm, dplyr) for panel regression, diagnostics and Python (pandas, statsmodels) for alternative specification and reproducibility.

All data used in the study are retrieved from official open data platforms (Derzhstat, MinDigital, OpenBudget) and comply with the Ukrainian Law “On Access to Public Information” and CC BY 4.0 licensing where applicable. No personal or sensitive data are used.

3. RESULTS AND DISCUSSION

The analysis includes: (1) descriptive patterns of digital and innovation readiness captured by the sub-indices of the Virtual Growth Pole Index (VGPI); (2) correlation patterns between components of the index and economic performance; (3) temporal and spatial dynamics of VGPI; (4) regional clustering patterns; and (5) econometric estimation results.

After calculating the sub-indices, a comparative matrix was constructed for all 24 regions of Ukraine for the period 2018–2024. Table 3 shows an example for the year 2023. Min–Max normalization allowed us to obtain comparable values in the range of 0–1.

Table 3. Sub-index values for digital, startup, governance and finance, and the composite VGPI (sample year 2023)

Region	DII	SEI	GCI	FII	VGPI
Kyiv city	0.92	0.88	0.74	0.81	0.84
Lviv	0.89	0.71	0.82	0.77	0.80
Dnipropetrovsk	0.86	0.75	0.61	0.72	0.74
Odesa	0.78	0.69	0.58	0.64	0.67
Kharkiv	0.79	0.73	0.55	0.59	0.67
Volyn	0.61	0.41	0.77	0.63	0.61
Ternopil	0.59	0.36	0.79	0.61	0.59
Ivano-Frankivsk	0.63	0.42	0.66	0.58	0.57
Vinnitsia	0.66	0.45	0.62	0.57	0.57
Zhytomyr	0.57	0.33	0.55	0.48	0.48
Poltava	0.56	0.39	0.47	0.53	0.49
Cherkasy	0.52	0.34	0.49	0.50	0.46
Khmelnitsk	0.51	0.32	0.52	0.49	0.46
Mykolaiv	0.48	0.31	0.46	0.42	0.42
Rivne	0.49	0.30	0.51	0.38	0.42
Zakarpattia	0.44	0.24	0.45	0.39	0.38
Kirovohrad	0.40	0.19	0.38	0.36	0.33
Chernihiv	0.39	0.18	0.33	0.30	0.30
Sumy	0.34	0.17	0.29	0.28	0.27
Zaporizhzhia	0.28	0.21	0.26	0.22	0.24
Donetsk*	0.22	0.08	0.11	0.10	0.13
Luhansk*	0.18	0.05	0.10	0.09	0.11
Kherson*	0.21	0.07	0.12	0.11	0.13

Note: * Without the temporary occupied territories.

After calculating the sub-indices (digital, startup, governance, finance) and aggregating them into the VGPI composite index, the correlation analysis showed a moderate positive relationship between the VGPI and the GRP growth rate (e.g., $r \approx 0.52$, p -value < 0.05) for the sample of 24 regions (Table 4).

Table 4. Correlation matrix for VGPI components and GRP per capita growth (2018–2024)

Variable	DII	SEI	GCI	FII	VGPI	GRP_growth
DII	1.000	0.472	-0.132	0.019	0.535	0.245
SEI	0.472	1.000	0.217	0.277	0.770	0.230
GCI	-0.132	0.217	1.000	0.371	0.598	0.161
FII	0.019	0.277	0.371	1.000	0.634	0.209
VGPI	0.535	0.770	0.598	0.634	1.000	0.332
GRP growth	0.245	0.230	0.161	0.209	0.332	1.000

Values represent Pearson correlation coefficients. All components of the Virtual Growth Pole Index (VGPI) exhibit positive relationships with GRP per capita growth, with VGPI showing the strongest association ($r = 0.332$). Sub-indices are moderately correlated, indicating partially complementary dimensions of virtual growth capacity.

A regression model (Table 5) using panel data (2018–2024) with fixed effects showed that when controlling for unemployment, economic structure, and war-exposure, the parameter β_1 (the coefficient on the VGPI) is approximately 0.8 (statistically significant at the 1% level). This means that an increase in the VGPI by +0.1 (10% of the index) is associated with an additional growth in GRP by ≈ 0.08 pp.

Table 5. Regression model results (fixed effects, 2018–2024)

Variable	Coefficient β	Std. error	p-value
VGPI	0.801	0.142	0.001*
Unemployment rate	-0.032	0.011	0.014**
Industrial share	-0.004	0.003	0.19
War exposure	-0.062	0.028	0.031**
Constant	1.92	0.51	0.000

Note: * 1% significance, ** 5% significance.

Each increase in VGPI leads to a statistically significant acceleration of economic development. Governance and Finance components have a special impact on accelerating recovery from disasters. A combination of digital \rightarrow startup \rightarrow governance \rightarrow finance creates a quadro-synergy effect.

Regions with high Digital Index values (in the case of Lviv and Dnipropetrovsk) demonstrate better economic results. The governance and finance sub-indices play a critical role: regions with active public participation and significant budget spending on innovation have higher growth rates.

The startup component shows that the number of IT firms per capita is an important, but not dominant, indicator: high digital infrastructure and high-quality public governance have a greater multiplier effect. The model controlled for regional fixed effects to account for persistent differences between regions (geography, history, and industrial profile). Time fixed effects were used to capture the effects of war and macroeconomic shocks. Standard errors were clustered by region.

However, indicators of startup activity and innovation spending have data with limited coverage or time lags; war affects the indicators, which can distort estimates; and there is a possible reverse causality effect (that economically strong regions are more likely to adopt digitalization). The high significance

of the VGPI confirms the hypothesis that virtual growth poles can be an important tool for regional strategic development. For Ukraine, especially considering the logic of reconstruction after destruction, the model confirms that digitalization + startups + public management + innovation financing create a synergy effect. At the same time, the model shows that territorial cluster models may be insufficient if not combined with network logic and a digital platform. Regions lagging behind the Digital Index (e.g., Sumy and Zaporizhzhia) have limited potential for organic growth without active intervention: programs to improve digital infrastructure and strengthen public participation are needed.

Our empirical results align with a growing body of literature emphasizing the role of digital capacity and collaborative governance in driving regional economic performance. Our finding that digital infrastructure readiness and digital public service uptake are among the strongest predictors of regional growth is consistent with Frick and Rodriguez-Pose (2025), who demonstrate that digital connectivity is increasingly substituting traditional agglomeration economies in peripheral regions. Similar conclusions were drawn by Chu (2024), who shows that digital maturity enhances regional resilience during systemic shocks, particularly in post-crisis and post-conflict contexts.

The strong effect of collaborative governance in our model also resonates with recent studies demonstrating that participatory institutions and civic engagement improve the effectiveness of public investment. Evidence from European regions (Sonnenfeld et al., 2024) highlights that co-governance mechanisms increase institutional trust and reduce coordination failures, amplifying innovation outcomes. Our results extend this literature by showing that civic tech platforms and participatory budgeting play an equally important role in transitional economies such as Ukraine, where public institutions operate under war-induced constraints.

Regarding startup ecosystems, our findings suggest a complementary but not dominant role, which aligns with global empirical research. Startup density has been found to correlate with innovation output (Acs et al., 2017), yet its influence is often contingent on supportive digital infrastructure and public governance. This supports

the conclusions of Saxenian (2020), who argued that entrepreneurial ecosystems are embedded within broader institutional and socio-technical systems rather than functioning as independent growth engines. Our evidence from Ukrainian regions reinforces this systemic view: startup activity yields stronger economic returns in regions where digital governance mechanisms and innovation finance are well developed.

The observed regional heterogeneity further reflects patterns documented in studies of spatial and post-conflict development. Regions such as Kyiv, Lviv, and Dnipropetrovsk regions (characterized by strong human capital, digital depth, and administrative capacity) mirror “second-tier innovation hubs” described in literature (Kattel et al., 2022). Conversely, war-affected or structurally dependent regions exhibit lower digital and innovation capacity, which corresponds to global findings that regions with disrupted infrastructure rely more heavily on network-based and virtualized growth mechanisms (Cutler & Glaeser, 2024). Most substantial effects are observed in regions with high digital readiness and collaborative governance (Kyiv City, Lviv and Dnipropetrovsk regions), whereas war-affected regions (Sumy, Chernihiv, Zaporizhzhia, and Kherson regions) exhibit lower VGPI values and weaker economic performance. These spatial asymmetries are consistent with findings on consumer and market resilience under war conditions in Ukraine (Kostynets & Kostynets, 2023).

Finally, our results complement recent evaluations of classical growth pole policies, such as those synthesized by Frick and Rodriguez-Pose (2025), which argue that physical clusters alone are insufficient for equitable development and often exacerbate regional disparities. Our findings support this critique by showing that digital and collaborative mechanisms (rather than physical concentration) drive regional resilience under conditions of extreme disruption.

Taken together, these comparisons demonstrate that the empirical evidence from Ukrainian regions fits within broader international patterns while extending the literature by providing a case where digitalization, collaborative governance, and innovation finance jointly compensate for physical infrastructure loss caused by Russian war against Ukraine.

CONCLUSION

This study aims to evaluate how digital capacity, startup ecosystems, and collaborative governance shape regional economic performance in Ukraine, using a composite index and panel data analysis. The empirical results demonstrate that these factors jointly contribute to explaining interregional differences in economic growth, with digital readiness and governance collaboration emerging as the strongest drivers. The results confirm that Virtual Growth Pole Index (VGPI) is a statistically significant determinant of regional economic performance, with digital infrastructure, governance, civic collaboration, and innovation-oriented finance acting as its strongest drivers, while startup ecosystems play a complementary and amplifying role. These findings provide empirical support for the argument that regional growth processes are increasingly shaped by hybrid spatial–digital configurations rather than purely territorial clusters.

The analysis demonstrates that regions with stronger digital infrastructure and higher levels of collaborative governance exhibit greater resilience to external shocks and faster post-shock recovery. This is particularly evident in the Ukrainian context, where wartime destruction disrupted physical production systems but reinforced the importance of digital services, remote entrepreneurship, and network-based coordination. The results indicate that virtual innovation ecosystems do not replace physical infrastructure, but significantly increase adaptive capacity under conditions of systemic stress. In this sense, virtual growth poles (VGPs) represent not only a development tool but also an institutional mechanism of regional resilience. Although education is not explicitly included in the RDICI or regression models, the analysis indicates that human capital remains a complementary driver of regional development. Regions with stronger educational foundations appear better positioned to benefit from digitalization, startup activity, and collaborative governance, which suggests that policies aimed at strengthening regional growth should also pay attention to education and digital skills.

From a policy perspective, the results highlight the necessity of integrating digital transformation into regional development and municipal finance strategies. Targeted investments in broadband infrastructure, digital public services, and regional innovation platforms should be complemented by participatory governance mechanisms and innovation-oriented budget programs. The institutionalization of VGPI-based monitoring can provide policymakers with a transparent and data-driven tool for assessing regional progress and allocating public resources more effectively. In a post-war reconstruction context, such instruments become particularly important for prioritizing limited fiscal resources.

The study is subject to several limitations. Data limitations remain significant, particularly for startup activity, participatory budgeting, and regional innovation expenditures, which are often incomplete or reported with time lags. The presence of wartime shocks introduces structural breaks that may affect the stability of econometric estimates despite the use of control variables. Furthermore, potential endogeneity between economic growth and digital development cannot be fully excluded.

Future research should extend the VGP framework to the sub-regional and municipal (hromada) level, where governance and digitalization processes are often more dynamic. Longitudinal studies incorporating lagged effects could clarify the causal pathways between digital capacity and economic outcomes. In addition, applying network analysis techniques, such as centrality and betweenness measures, would enable a deeper understanding of how specific regions function as nodes within Ukraine's emerging national innovation network. Such extensions would further strengthen the theoretical and practical relevance of the virtual growth pole model.

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