BRATISLAVA UNIVERSITY OF ECONOMICS AND BUSINESS

FACULTY OF ECONOMICS AND FINANCE

SELF-REPORT OF DISSERTATION

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Self-report of Dissertation

The impact of digitization on economic growth: assessing role of digital infrastructure in the digital age

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1. An overview of the current status of the issues addressed in the dissertation at home and abroad

The literature on digital infrastructure, economic growth, and regional development highlights increasing significance of technological innovation in supporting productivity gains, innovation, and economic growth. Understanding how economies grow over time requires theoretical models that explain roles of capital accumulation, labour inputs and technological change. Two foundational but contrasting theoretical schools have shaped the study of long-run growth, in economic literature, the exogeneous and endogenous growth theory.

Theoretical foundations of economic growth and technological change

Traditionally, the Solow-Swan model (Solow, 1957) framed technological progress as an exogenous factor needed to prevent diminishing returns from capital accumulation. In this model, technology enhances labour productivity without being explicitly modelled. It was shown that up to 87.5% of U.S. economic growth in the early 20th century stemmed from technological change (Munnell, 1992). The emergence of endogenous growth theory in the late 1980s marked a paradigm shift.

Romer (1990) and Lucas (1988) argued that technological innovation arises from deliberate economic activity, such as R&D and human capital investment. In Romer's model, knowledge is a non-rivalrous, partially excludable good, yielding increasing returns and allowing for sustained growth without external technological shocks. These models paved the way for considering ICT and digitization not just as tools but as integral inputs in growth models.

Moreover, Schumpeterian growth theory (Aghion & Howitt, 1992) introduced the concept of creative destruction, wherein entrepreneurs continuously replace outdated technologies with newer innovations.

These theoretical contributions provide the justification for treating ICT and digitization as core variables in empirical growth models, especially in variations of the Cobb-Douglas production function, where they can improve total factor productivity and complement labour and capital inputs.

Digitization, through information and communication technologies (ICT), is increasingly recognized as a General-Purpose Technology (Bresnahan & Trajtenberg, 1995). GPTs have three main characteristics: they are widely used, capable of ongoing technical improvement, and enable complementary innovations across sectors. The transformative power of ICT, as highlighted by Brynjolfsson and McAfee (2014), is likened to the earlier industrial revolutions, reshaping productivity paradigms.

In line with this, the dissertation thesis emphasizes that ICT alone does not guarantee growth; its effectiveness is conditional upon complementary factors such as human capital, digital literacy, legal frameworks, and infrastructure reliability. These complements, emphasized by the World Bank (2016), include education systems, institutional quality, and competitive markets that enable innovation diffusion and productivity gains.

Digital infrastructure in modern production functions

To measure the effect of digitization on growth, economic analysts tend to apply standard production function methodology by adding digital infrastructure and ICT capital as a specific contribution. In the classical Cobb-Douglas production function, output is represented as a product of physical capital, labour and technological advancements are captured as a TFP term. Recent practices include augmenting the production function with other additional inputs such as ICT capital or infrastructure, thus attributing their unique bearing on production.

Papaioannou & Dimelis (2007) explored how digitization progress contributes to productivity growth. By employing a Cobb–Douglas production function with multiple inputs, their adopted econometric specification for the model is as follows:

$$Y_{it} = A\, exp^{\lambda t}(L_{it})^{\alpha}(DIGI_{it})^{\beta}(K_{it})^{\gamma}exp^{\varepsilon it}$$

In this equation Y_{it} represents the real GDP, i denotes the country and t refers to the time. Additionally, L_{it} represents the labour force size which is measured by the number of workers. Further, K_{it} denotes the capital stock measured as gross fixed capital formation, the percentage of the GDP and $DIGI_{it}$ is representing part of the capital being invested in the digitization infrastructure, expanded use of internet. Also, $exp^{\lambda t}$ stands for the exponential function and A denote the labour-augmenting factor. In the above a Cobb–Douglas production function with multiple inputs, t is a time trend while the coefficients such as α, β, γ are the slopes or elasticities of labour force, digitalization-capital and non-digitalization capital respectively.

Further, ε_{it} denote the error term which is assumed to follow standard econometric assumptions (Papaioannou & Dimelis 2007). Papaioannou & Dimelis (2007) estimated an augmented production function for both developed and developing 42 countries and found that ICT capital positively and significantly contributes to the growth of labour productivity with the impact notably stronger in developed economies.

From an output perspective, treating digital infrastructure as an investment means that policies or other factors which increase the availability of internet, mobile networks or computing devices will in turn increase the GDP of a country assuming other variables remain unchanged. This reasoning explains why many growth regression models started including ICT metrics and independent variables. Some cross-country panel regressions, where the number of broadband subscriptions and mobile phone access rates were included, often showed a significantly positive correlation (Edquist et al., 2018); Vu, 2011; Birinci & Kirikkaleli, 2021).

Empirical findings on digitization-growth nexus

Several cross-country panel data studies have provided an extensive indication on the relationship between the digitization of digital infrastructure systems and economic growth. Internet and mobile technology increases are empirically found to be associated with an increase in GDP per capita. As a rule, the evidence confirms the strong influence of digitization on growth, gaining further support from the improvements in broadband and mobile connectivity in both developed and developing economies that increases productivity, market expansion, and efficiency improvements (Czernich et al., 2011, Qiang et al., 2009). This section provides some of the most relevant findings from global and multi-country analyses to demonstrate the impact of different aspects of digital infrastructure on economic performance, including broadband and mobile networks.

The importance of broadband infrastructure in economic growth

Earlier evidence arises from analyses of general telecommunication infrastructure: Röller & Waverman (2001) found that telecommunication infrastructure has a significant impact on GDP growth within 21 OECD countries examined over two decades using a two-stage instrumental variable approach. They also reported that telecom network effects became meaningful only after a critical average penetration of roughly 40% was attained (Röller & Waverman, 2001). In the era of broadband, several studies confirmed substantial growth from internet connectivity. Czernich et al. (2011) studied broadband adoption across 25 OECD countries and concluded that a 10-percentage point increase in broadband penetration is associated with a 0.9–1.5 percentage point increase in GDP per capita. Notably, countries with low levels of connectivity initially gained the most from accelerated broadband adoption (Czernich et al., 2011), which points to the existence of diminishing returns in connected economies and a catch-up effect for lagging economies. Qiang et al. (2009) similarly showed that in low- and middle-income countries, a 10% increase in access to broadband led to approximately 1.3% higher GDP growth, further validating that the diffusion of internet holds economic value even outside the OECD countries.

Castaldo et al. (2016) also documented that the development of broadband networks is beneficial for economy, both in the short and long term for the OECD countries, highlighting the value of high-speed internet infrastructure sustaining growth. Other researchers focusing on OECD countries also estimated economic importance of broadband access for the output per capita growth (Atif et al., 2012). The economic reason for these consequences is that broadband access increases productivity due to the new business models that can be adopted; the greater and more efficient communication, and innovation enabled. Indeed, broadband-accessed technologies like e-commerce and digitally managed supply chains have been attributed with enhancing productivity and market access at the firm level, which in turn has led to economic growth on a macroeconomic scale (Czernich et al., 2011; Tranos, 2012).

Mobile telecommunications and their link to economic development

Mobile telephones and mobile internet are growth determinants (Bahrini & Qaffas, 2019). The expansion of mobile networks extending from simple cellular phones to mobile broadband has enabled several nations to skip the traditional infrastructure. Wawerman et al. (2005) founded that mobile phone diffusion increased economic growth in developing countries, sometimes even doubled previously estimated rates of growth. Later, Gruber & Koutroumpis (2011) related the increase in mobile telecommunications to GDP growth, though their impact was rather negligible in very low penetration (often low income) countries, supporting the notion that some basic level of user population is necessary to access network externality benefits.

As mobile broadband became available, its growth effects persisted: Edquist et al. (2018) found that a 10% increase in mobile broadband subscriptions resulted in approximately a 0.8% increase in GDP per capita in 135 countries. Their IV-based global analysis highlights the fact that the economic benefits of having access to the internet is not restricted to fixed broadband, as wireless internet access through 3G/4G networks also has considerable growth impacts (Edquist et al., 2018). Even the most developed economies continue to experience growth effects from the use of mobile and the internet. As an example, Birinci & Kirikkaleli (2021) studied G7 countries and found that mobile telephone usage and broadband usage both have a significant impact on GDP growth in the long-run, and so digitization still matters even at the technology frontier. Similarly, studies conducted for broad sets of countries in the 2000s, such as Vu (2011)'s which covered 102 economies, found a strong correlation between the level of ICT penetration, measured by mobile subscriptions and internet users, and economic growth. All these studies help to strengthen the argument that having the ability to communicate, whether through voice calls or sending data over the internet, drives growth in several countries regardless of their level of development (Sarangi et al., 2020; Kurniawati, 2020).

Digital literacy and human capital in economic development

Digital infrastructure alone is not sufficient to ensure economic benefits from digitization. A digitally literate and skilled workforce is essential for realizing the full growth potential of ICT diffusion. Human capital, proxied as gross school enrollment (Barro, 1996), enables individuals to effectively use digital tools, adapt to technological change and contribute to innovation processes. Several studies have demonstrated that digital literacy amplifies the economic returns on broadband investments by improving innovation, supporting knowledge diffusion, and workforce adaptability.

Barro (1991) was among the first who has empirically established a positive link between education and economic growth in a large cross-country study. More recent research emphasizes the complementary role of education in amplifying the returns from digitization. Myovella et al. (2020) show that human capital, measured through school enrollment, and educational attainment significantly moderates the relationship between ICT and economic growth in both OECD and Sub-Saharan African economies. Égert et al. (2009) emphasize that diffusion of telecommunications infrastructure positively impacts long-term economic growth in G20 countries, suggesting that digital infrastructure alongside human capital plays a key role in enhancing economic performance. In Asian context, Widarni & Bawono (2021) founded that an increase in human capital, particularly through education, significantly affects economic growth in Indonesia. Raeskyesa & Lukas (2019) revealed that ICT indicators have a significant positive impact on economic growth along with physical and human capital in 8 Asian countries.

Bukht & Heeks (2018); Tsaurai & Ndou (2019) discussed the role of digital infrastructure and its impact on economic growth in developing countries. They highlight that digital infrastructure is a critical component for the growth of the digital economy and human capital in terms of digital skills is a key element in using digital infrastructure for economic growth. Habibi & Zabardast (2020) emphasized that the economic impact of digital infrastructure is most pronounced in regions with higher educational attainment and stronger digital skills.

The adaptability of the workforce has emerged as an additional key component for increasing the economic benefits of broadband. Bresnahan et al. (2002) stated that firms that restructured their management to incorporate ICT (information and communication technology) tools had more productivity gains. The level of employee digital skills highly determines the application of information technology in a business (Cetindamar, Abedin, Shirahada, 2021).

Regional disparities in digital infrastructure impact

While digital infrastructure is widely acknowledged as a driver of economic growth, its effects are not uniform across regions. The literature highlights significant disparities based on countries' development levels, digital readiness, and policy environments. Two competing perspectives dominate the academic discusisons. The first emphasizes a leapfrogging hypothesis, suggesting that less-developed countries may experience higher marginal gains from ICT investments (Waverman et al., 2005; Czernich et al., 2011; Adeleye & Eboagu, 2019). This view is supported by evidence from Sub-Saharan Africa and ASEAN countries, where improvements in mobile penetration and broadband access have been associated with substantial gains in GDP per capita (Haftu, 2019; Ahmed & Ridzuan, 2013; Goldbeck & Lindlacher, 2024).
Contrastingly, other studies argue that advanced economies benefit more in absolute terms from digital infrastructure due to their superior complementary assets—such as human capital, institutions, and innovation ecosystems (Rhiel, 2018; Niebel, 2018). These findings challenge the leapfrogging narrative and imply that without strong supporting conditions, infrastructure alone may yield limited returns in developing contexts.

Evidence from Central and Eastern Europe (CEE) offers different insights. Tranos (2012) and others confirm that broadband penetration supports economic convergence in the region, but its effectiveness depends on accompanying reforms and investments in skills and governance (Saranggi & Pradhan, 2021; Novikova et al., 2022). Estonia and Poland are cited as successful examples where integrated strategies, combining broadband rollout with digital literacy and education reforms, narrowed regional digital divides and enhanced competitiveness.

Urban-rural disparities emerge as a persistent theme. While urban areas benefit from dense, high-speed networks, rural regions face limited coverage, lower adoption, and weaker economic outcomes (Ndubuisi et al., 2021; Kolodynskyi et al., 2018). This digital divide constrains e-commerce, remote work, and SME development. National programs such as Poland's "Digital Poland," Estonia's "Broadband for All," and Hungary's "Digital Success Program" demonstrate that targeted interventions, especially in rural infrastructure and human capital, are critical for inclusive growth.

Overall, the literature suggests that while digital infrastructure can catalyze development, its effectiveness hinges on context-sensitive strategies that address not only access, but also institutional, educational, and geographic constraints.

The literature review identifies a research gap in applying empirical models to EU13 economies. This dissertation thesis solves it by using broadband and mobile subscriptions as instrumental variables (via PCA) in a two-stage least squares (2SLS) model to estimate their impact on GDP per capita—thus contributing novel insights to the field.

2. Aim and focus of the dissertation

The primary objective of this thesis is to study the impact of digital infrastructure on the economic growth in Slovakia compared to other EU regions. Using advanced econometric methods, we seek to quantify the impact of digital infrastructure (including internet penetration, fixed broadband subscriptions, and mobile cellular subscriptions) on economic performance. The research also seeks to pinpoint regional variation in the impact of digitization and to develop recommendations specifically targeted at policy measures intended for full utilization of the potential contribution of digital transformation in Slovakia.

Additionally, aim of this dissertation thesis is to explore impact of digitization on economic growth in EU-13 countries by examining the role of digital infrastructure in period from 2000 - 2023 using a Cobb-Douglas production function empirical framework and econometric model. The outlined aim intends to address unresolved questions about the long-term impact of broadband penetration, mobile connectivity on economic performance in the region. These objectives align closely with the methodological framework presented later in this thesis. This study is structured around the following partial objectives:

- addressing gaps in empirical research on digital infrastructure's role in Slovakia's economic growth
- providing a comparative perspective across EU regions to highlight best practices and areas for improvement
- investigate the relationship between digital infrastructure and economic growth in CEE countries
- evaluate the impact of broadband and mobile penetration on GDP growth

The objectives presented provide a foundation for developing four research questions that will guide the dissertation’s analysis. To achieve objectives of this dissertation, we will answer following research questions:

RQ 1: What is the impact of digital infrastructure on economic growth in Slovakia?

RQ 2: How does Slovakia compare to other EU regions in its impact of digital infrastructure on economic growth?

RQ 3: To what extent does the diffusion of digital infrastructure causally impact GDP per capita in EU-13 countries?

RQ 4: How effective is a composite indicator of digital infrastructure as an instrumental variable in isolating the causal impact of digitization on economic growth?

3. Methodology of work and research methods

Digitization has become one of essential determinants of economic and social progress. Advanced infrastructure and a higher rate of technology adoption have caused significant gains in productivity and economic growth in developed economies (Brynjolfsson & Hitt 2000; Oliner & Sichel 2000). However, developing countries do face some limitations in investment and technological penetration (Dewan & Kraemer 2000; Habibi & Zabardast 2020). Furthermore, the methodological improvements, such as more sophisticated digitization and economic growth frameworks (Daveri 2002), point out that widespread digitization and the use of the internet in communications drive productivity while pointing to different outcomes, such as individuals using the internet's limited impact and unemployment concerns among unskilled workers (Aghion et al. 1998).

Previous literature examined the nexus between digitization and economic growth found the association to be significant in the short run; however, in the case of EU-13, it has failed to establish a long-run consistent causality. In addition, Brynjolfsson and McAfee, (2014) claims that digitization is apparently affecting the economic growth, there remains the challenge of assessing the direct cause, particularly arising from potential endogeneity (Czernich et al. 2011; Tranos 2012). The reason behind this may be reverse causality, i.e., economic growth determines the level of digitization, or perhaps omitted variables create both. Therefore, the issue of endogeneity must be addressed if credible estimates of causality must be obtained. This research will effort to solve the endogeneity issue with the help of instrumental variables approach. This approach will test the effect of digitization, measured by the percentage of active internet users, on economic growth, measured by the

GDP per capita, for the 13 members of the European Union between 2000 and 2023.

Thus, to use the full potential of digitization, concentrated strategies, like infrastructure building and policy support are required for economic growth and reducing disparities among regions. Therefore, the major objective of this study is to analyse the role of digital infrastructure on the economic growth of EU-13. Hence, as per the research questions and hypotheses, the subsequent section attempts to elaborate the theoretical and empirical specification being pursued.

This study relay of the theoretical framework being adopted by Papaioannou & Dimelis (2007) to investigate how digitization progress contributes to productivity growth. The framework is based on the using of a Cobb–Douglas production function with multiple inputs. The adopted econometric specification for the model is as follows:

$$Y_{it} = A\, exp^{\lambda t}(L_{it})^{\alpha}(DIGI_{it})^{\beta}(K_{it})^{\gamma}exp^{\varepsilon_{it}} \quad (1)$$

In the equation above, Y_{it} represents the real GDP, i represents the country and t represent the time. Additionally, L_{it} denotes the labour force size which is measured by the number of workers. Further, K_{it} represents the capital stock which is measured as gross fixed capital formation as percentage of the GDP and $DIGI_{it}$ is representing part of the capital being invested in the digitization infrastructure, expanded use of internet. To clarify, $DIGIit$ represents the intensity of digital adoption (individuals using the internet) and is not a direct component of physical capital (Kit). It reflects the effective utilization of existing digital infrastructure by the population. Hence, digital infrastructure investment (proxied by fixed and mobile broadband subscriptions) influences DIGI indirectly, but DIGI is modelled as a separate input in the production function, not as a component of K. To avoid confusion, all references to 'digitization capital' have been harmonised as 'digital infrastructure usage'. There is no double-counting, and Kit continues to refer strictly to non-digital gross fixed capital formation. Also, $exp^{\lambda t}$ stands for the exponential function and A denote the labour-augmenting factor. In the above a Cobb–Douglas production function with multiple inputs, t is a time trend while the coefficients such as α, β, γ are the slopes or elasticities of labour force, digitalization-capital and non-digitalization capital respectively. Further, ε_{it} denote the error term which is assumed to follow standard econometric assumptions (Papaioannou & Dimelis 2007).

By taking logarithms and assuming constant returns to scale, the relationship is transformed to represent output per worker as a function of tech and non-tech capital-to-labor ratios:

$$\ln(y_{it}) = c + \lambda t + \beta \ln(DIGI_{it}) + \beta \ln(K_{it}) + \varepsilon_{it} \quad (2)$$

This transformation allows to estimate the elasticities of labour, digitization, and capital, and to interpret these elasticities as the impact of each factor on productivity growth.

Estimation method

This analysis of panel data involves addressing the relationship between unobserved factors affecting the dependent variable, distinguishing between those that remain constant and those that change over time. Incorporating digitization, represented by use of internet into the model, raises endogeneity concerns, as this variable correlates with the error term and may bias the result of our model. To address these issues, we applied an extended two stage least square (2SLS) instrumental variable (IV) estimation method for panel data.

In the first stage, all exogenous variables, including instruments, are regressed for each endogenous explanatory variable. This process isolates the portion of the endogenous variable uncorrelated with the error term. Although fixed broadband and mobile cellular subscriptions could be correlated with GDP in levels, they serve here as instruments for internet usage, not for GDP directly. Their role is to proxy physical access to digital infrastructure, thus affecting economic performance only through their effect on digitisation. The exclusion restriction is strengthened through country fixed effects, macroeconomic controls (GFCF, GSE, TO, etc.), and lagged instrument checks. Together these confirm that the instrumented variation in digitisation is orthogonal to economic output shocks. Specifically, the following first-stage model is estimated using the 2SLS method:

$$DIGI_{it} = c + \theta Z_{it} + \psi W_{it} + \delta_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Here, $DIGI_{it}$ represents the endogenous variable for country i at time t, influenced by the instrumental variable Z_{it} and additional exogenous variables W_{it}. The terms δ_i and λ_t account for country-specific and time-specific effects, respectively, while ε_{it} is the error term. This process identifies exogenous variation in $DIGI_{it}$ while controlling for both time-invariant characteristics and common time-variant shocks.

In the second stage, the predicted values from the first-stage regression serve as instruments in estimating the relationship between the dependent variable and the exogenous variables. The second-stage model is expressed as:

$$y_{it} = \alpha + \beta \widehat{DIGI}_{it} + \psi W_{it} + \delta_i + \lambda_t + \epsilon_{it} \quad (4)$$

In this equation, y_{it} represents the dependent variable for country i at time t, regressed on $DIGI_{it}$, the predicted values from the first stage, to evaluate the influence of digitization on productivity. Exogenous variables W_{it}, along with country and time-specific effects denoted by δ_i and λ_t, are included.

To ensure that the instrumental variables meet the exclusion restriction, the study follows a multi-layered validation strategy. Fixed broadband subscriptions and mobile cellular subscriptions are chosen not because they directly affect economic growth, but because they determine the population's potential access to digital services, thus influencing GDP only through digitisation. These instruments do not impact GDP per capita through alternate channels such as investment, labour force participation, or trade, as all such macroeconomic factors are already controlled for in the model.

Furthermore, to strengthen the causal interpretation, lagged values of both instruments (t−1) are used in a robustness check. The elasticity of DIGI on GDP remains nearly identical (0.021 vs. 0.022), and the Cragg-Donald F-statistic (13.8) confirms that the instruments are sufficiently strong. The Hansen J test yields a p-value of 0.20, which supports the assumption that the instruments are exogenous. These formal diagnostic tests validate that broadband and mobile subscriptions satisfy both the relevance and exclusion requirements for instrument validity.

Data and variables

The first part of the research sample includes the 27 EU member countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. For Slovakia, the empirical unit is the country–year observation. The balanced EU-27 panel therefore contains 34 Slovak data points spanning 1990-2023, while the EU-13 growth subsample supplies a further 24 Slovak observations for 2000-2023.

Descriptive statistics confirm that variation is not purely cross-sectional: the within-Slovakia standard deviation of the DIGI index equals 35.2. This depth ensures that the national coefficient is identified from genuine time-series movement, not noise.

To assess the consequences brought about by digitization on economic growth, relevant indicators for the period 1990-2023 that is, a period of 33 years, were retrieved from WDI databases in 2024. The indicators proxied economic growth, the level of digital infrastructure, and other conditions at a macroeconomic level. Economic growth was proxied by GDP per capita at constant 2015 prices. The dependent variable used is the logarithm of GDP per capita, capital stock is measured as the gross capital formation as percentage of GDP and human capital is measured as the gross secondary school enrolment. Moreover, the data to represent the role of fiscal policy and government comes from general government final consumption expenditure as percentage of GDP, and trade openness is measured as the sum of exports and imports of goods and services measured as a share of gross domestic product.

The second part of the research employed the sample of 13 EU countries - Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia. To assess the effect of the digital infrastructure on economic growth, a set of indicators was collected in 2024 from the World Bank World Development Indicators (WDI) databases for 24-year period

(2000-2023). These indicators assess economic growth, digital infrastructure, and macroeconomic conditions.

All continuous variables used in the econometric estimations have been log-transformed where appropriate to allow elasticity-based interpretation of coefficients. Specifically, GDP per capita (GDPPC), digitisation (DIGI), gross fixed capital formation (GFCF), and school enrolment (GSE) are expressed in natural logarithms. The results throughout the regression tables should therefore be interpreted as percentage changes. For example, a 1% increase in internet usage (DIGI) leads to an estimated 0.02–0.03% increase in GDP per capita. Unit labels and log transformations are clearly annotated in Table 2 and footnotes of regression tables.

4. Structure of the dissertation

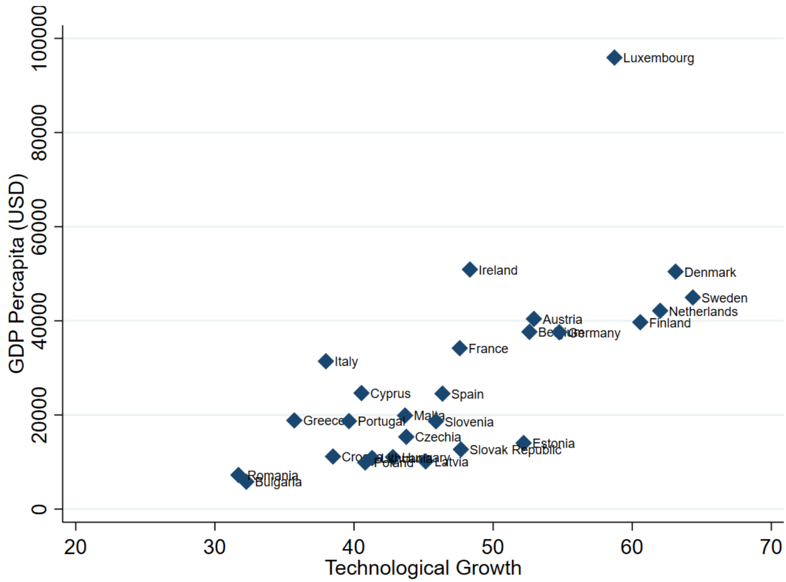
This dissertation thesis with title "Impact of digitization on economic growth: assessing role of digital infrastructure in the digital age" is organized into seven main chapters starting with Introduction chapter where I describe the motivation and focus of work. Following chapter describe the literature review and presents scientific knowledge and research results relevant to this topic in more detail. It covers classical and endogenous growth theories, concept of ICT as general-purpose technology and important studies linking broadband and mobile infrastructure to GDP growth. Special attention is given to the role of human capital, digital literacy and institutional readiness as mediating variables in digitization-growth nexus. Theoretical part of this thesis is followed by aim, objectives and hypotheses of the research. It defines the main research question, how digital infrastructure affects economic growth, and identifies four specific hypotheses related to broadband penetration, mobile connectivity, human capital and regional differences. This chapter justifies the relevance of focusing on Slovakia and EU-13 region as well. Next chapter details the methodological approach, introduces an augmented Cobb-Douglas production function and employs panel data econometric models over the period from 2000-2023. This research uses two-stage least square (2SLS) instrumental variable estimation to solve endogeneity concerns, with broadband and mobile subscriptions as instruments. Data are collected from World Bank, Eurostat and national datasets. Chapter 5 presents empirical results, compares Slovakia with EU-27 and performs a focused analysis on EU-13 countries. Findings are described as a result from regression analyses. Results are followed by Discussion, where implications of findings are discussed. This part of thesis reflects on theoretical contributions to endogenous growth theory, offers managerial insights and identifies limitations as data availability and regional heterogeneity. Recommendations for future research and policy development are proposed as well, particularly in areas of digital literacy and infrastructure policy. Finally, last chapter concludes the thesis, summarizes core findings and their relevance for economic theory and digital development policy as well.

5. The results of the work

Based on the methodology specified, results are described based on regression models. Results are divided into two main subchapters. The first part examines the role of digitization infrastructure process on the economic growth in Slovakia and its comparison with EU27 countries. The second part explores to what extent does the diffusion of digital infrastructure causally impact GDP per capita in EU-13 countries. Both parts are supported by appropriate diagnostic tests.

Figure 5, the scatter plot describes a positive correlation of digitization versus GDP per capita in European countries. In general, with the higher level of digitization, the higher the GDP per capita; this means that digitization advancement affect economic prosperity. However, the trend is not perfectly linear, meaning there are other factors that come into play. If taking generally, Slovakia stands in the middle left of the plot, meaning an average level of digitization considering all the countries of Europe but a relatively low level of GDP per capita.

Figure 1. The relationship of GDP per capita and digitization (1990-2023)



Source: author calculation

<u>Pairwise correlation matrix and Variance inflation factor test</u>

For a more accurate result of analysis, correlation between variables was checked. Normally, for further regression analysis, the correlation above 0.5 between the two variables is risky. In the case of our variables, its correlation is acceptable. In general, correlation matrix suggests that countries with higher GDP per capita are wealthier and have better mobile, broadband, and digital infrastructure, and even human capital; they also tend to have more open economies. There are clear positive associations between trade openness, digital infrastructure, and broadband access. Government expenditure on the other side shows mixed and sometimes negative relations with the other factors. Population growth, GDP growth, and human capital show partly very important relations to economic prosperity and digital infrastructure. These factors belong to the standard determinants responsible for the development of a nation.

Also, the VIF values are generally very low; all are below 2, indicating that this dataset does not have multicollinearity issues. All variables have a 1/VIF greater than 0.5, suggesting they each explain a reasonable amount of unique variance. Having a mean VIF of 1.373, it's safe to conclude that the scale variables bear some reasonably high degrees of independence from one another such that, in any case, regression models run using this data are unlikely to suffer much from multicollinearity problems.

Table 1. Variance inflation factor

	VIF	1/VIF
TO	1.709	.585
DIGI	1.566	.639
GGFCE	1.527	.655
GSE	1.459	.685
GFCF	1.302	.768
PG	1.293	.773
UNEMP	1.261	.793
GDPG	1.136	.881
Slovak DIGI	1.105	.905
Mean VIF	1.373	.

Source: author calculation

The results in this study are deduced from the models specified earlier using the methodology outlined in the previous section. The section on results is subdivided into three sections presenting the findings in a clear and organized manner in table 8, 9, and 10. The interpretation of the empirical results follows the theoretical model with, among other things, a focus on the consistency and robustness of the 2SLS estimates. The result is further strengthened with application of robust standard due to the possible presence of heteroscedasticity or any other form of model misspecification. Further, the result for under-identification and weak instrument tests such as Anderson LM and Cragg-Donald remain essential diagnostics and it provide estimates that are validating the certainty of IV regression models being used. These altogether prove the appropriateness of the used instruments in 2SLS regression. By applying different econometric techniques and robustness checks, this analysis enables an integrated overview of the role that digital infrastructure plays in driving economic growth, with particular attention being paid to the case of Slovakia and its European counterparts.

Table 2. First stage regression result

VARIABLES	(1) SK	(2) V4	(3) WEU	(4) NEU	(5) SEU	(6) EEU	(7) SEEU	(7) EU
FBS	0.593**	1.301***	0.896***	1.028***	1.325***	0.957***	1.096***	1.005***
	(0.235)	(0.0874)	(0.0646)	(0.0600)	(0.0611)	(0.0803)	(0.114)	(0.0322)
MCS	0.586***	0.287***	0.380***	0.233***	0.165***	0.242***	0.139***	0.263***
	(0.0627)	(0.0199)	(0.0217)	(0.0219)	(0.0171)	(0.0226)	(0.0411)	(0.0109)
GFCF	-0.130	-0.315**	1.260***	-0.0521	-0.115	-0.840***	-0.181	-0.320***
	(0.318)	(0.158)	(0.370)	(0.107)	(0.153)	(0.148)	(0.214)	(0.0690)
GSE	1.184***	0.369***	-0.0164	0.0185	0.0168	0.159	0.238*	0.0545*
	(0.377)	(0.133)	(0.0546)	(0.0411)	(0.0657)	(0.112)	(0.122)	(0.0312)
GDPG	-0.0854	-0.0737	-0.118	-0.187**	-0.231**	-0.0334	-0.0598	-0.155***
	(0.153)	(0.111)	(0.206)	(0.0843)	(0.101)	(0.112)	(0.137)	(0.0578)
UNEMP	0.783**	0.0877	0.633*	-0.365***	-0.204	-0.0897	-0.0900	-0.441***
	(0.367)	(0.157)	(0.321)	(0.136)	(0.138)	(0.184)	(0.268)	(0.0824)
TO	-0.0756	-0.0282	0.0488**	0.147***	0.100***	0.198***	0.222***	0.138***
	(0.0674)	(0.0431)	(0.0236)	(0.0299)	(0.0353)	(0.0435)	(0.0618)	(0.0150)
PG	2.761	-2.100*	2.184	1.138	-1.591**	-1.445	-0.284	-1.559***
	(4.867)	(1.163)	(1.406)	(0.890)	(0.631)	(1.090)	(1.055)	(0.497)
GGFCE	0.898*	-1.105***	0.398	-0.748***	-0.683**	0.454	0.210	-0.411***
	(0.509)	(0.346)	(0.526)	(0.281)	(0.280)	(0.345)	(0.373)	(0.145)
Constant	-124.5***	2.646	-37.83***	21.79**	18.61	-13.39	-25.44	11.86**
	(40.29)	(14.40)	(13.73)	(9.704)	(11.49)	(13.92)	(19.05)	(5.208)
Observations	34	136	204	238	238	204	136	918
R-squared	0.993	0.979	0.977	0.967	0.972	0.955	0.944	0.953
Number of countries	1	4	6	7	7	6	4	27

*** *p<0.01*, ** *p<0.05*, * *p<0.1*

Source: author calculations

Table 8., presents the results of the regression in the first stage of the 2SLS approach. It instruments the endogenous digital infrastructure variable with mobile cellular subscriptions and fixed broadband subscriptions, as described in the methodology.

According to table 8., first-stage 2SLS regression results confirm the heterogeneous effect of FBS and MCS on the state of digital infrastructure across the selected regions. In the case of Slovakia (SK), the coefficients for FBS and MCS are positively significant, with values of 0.593 and 0.586, respectively, hence proving that an increase in the mentioned infrastructural measures such as FBS and MCS leads to a significant enhancement of the digital transformation process. In the V4 region, the effect is very strong (1.301 coefficient), underlining the core role of the broadband infrastructure to increase digitization within that group. Again, for Western European Union (WEU) and Northern European Union (NEU), coefficients related to FBS are statistically significant and positive (0.896 and 1.028, respectively), putting an emphasis on the theme of how important the expansion of broadband has been to digital infrastructure in these regions. Again, the MCS effect is positive and significant throughout all regions, showing that mobile connectivity keeps acting as an essential driver of digital infrastructure, particularly in those areas-for instance, V4 and WEU-where mobile networks are a complement to fixed broadband for digital growth. While FBS still shows a positive and significant effect in both Southern Europe (SEU) and Eastern Europe (EEU), the magnitude of MCS is relatively low in both regions, with 0.165 and 0.242, respectively, which might suggest that mobile infrastructure alone cannot be so potent in driving digitization for such regions. For Southeastern European Union (SEEU), FBS is still high, recording 1.096, which explains that the increase in broadband does matter, while the coefficient MCS is lower, reporting 0.139 compared to other regions, which may be a limitation of the role played by mobile infrastructure to digital transformation.

These results therefore mean that FBS and MCS both stand at important points when it comes to digital infrastructure, but each is important in different regions. The effects of the two types of infrastructure are stronger in more developed regions, such as V4 and WEU, with the particularly important role of broadbands, though for less-developed regions these effects become more moderate, what may suggest that it is necessary for them to further develop digital transformation with more equal balance between both types of the above-mentioned infrastructure.

Table 3. Pooled comparative regression results on the productivity growth

VARIABLES	(1) OLS	(2) Fixed Effect	(3) 2SLS
DIGI	0.00537***	0.00500***	0.00497***
	(0.000579)	(0.000193)	(0.000850)
GFCF	0.00505	0.00511***	0.00510*
	(0.00362)	(0.00113)	(0.00268)
GSE	0.0157***	0.00318***	0.00319***
	(0.00117)	(0.000485)	(0.00118)
GDPG	-0.000163	0.00325***	0.00324*
	(0.00354)	(0.000899)	(0.00176)
UNEMP	-0.0104**	-0.0188***	-0.0188***
	(0.00414)	(0.00131)	(0.00365)
TO	0.000451	0.000783***	0.000802
	(0.000365)	(0.000245)	(0.000930)
PG	0.429***	0.0113	0.0113
	(0.0225)	(0.00772)	(0.0227)
GGFCE	-0.0172***	-0.0101***	-0.0100
	(0.00497)	(0.00229)	(0.00910)
Slovak_DIGI	-0.00270*	0.00222***	0.00222**
	(0.00152)	(0.000629)	(0.000986)
Constant	8.219***	9.497***	9.494***
	(0.183)	(0.0832)	(0.288)
Observations	918	918	918
R-squared	0.613	0.813	0.813
Number of countries	27	27	27
Under identification and weak instrument tests			
Anderson L $\chi 2$ stat			16.67
p-value			0.0231
Cragg-Donald F stat.			13.54

**** $p<0.01$, ** $p<0.05$, * $p<0.1$*

Source: author calculations

According to table 9., the second subsection provides the regression outcomes for OLS, FE, and 2SLS models. A key feature of this stage is the inclusion of an interaction term between the Slovakia dummy variable and digital infrastructure. This interaction allows us to explore the specific effects of digital infrastructure on Slovakia's economic growth trajectory, particularly in comparison to other EU regions. While OLS and FE regressions provide useful initial insights, the final analysis will rely on the 2SLS estimation method to address endogeneity concerns and produce more robust and consistent results.

From the OLS, FE, and 2SLS estimates in table 9., it can be seen that, regardless of specification, the relation of digital infrastructure to economic growth is consistently positive and statistically significant. The coefficients are 0.00537, 0.00500, and 0.00497, respectively, for the OLS, FE, and 2SLS estimations at 1% significance levels. These findings also mean that the impact of digital infrastructure on economic growth is quite strong, while the magnitude decreases a little from OLS to the 2SLS model. That means, in controlling for endogeneity using 2SLS, the estimate of the impact of digital infrastructure becomes more reliable.

The interaction term for Slovakia is denoted by Slovak_DIGI. With this interaction term, there can be significant understanding of how digitization affects Slovakia economic growth. Based on the OLS model, the coefficient for Slovak_DIGI is negative and marginally significant at 10% (-0.00270), which may imply that, without controlling for endogeneity, digital infrastructure in Slovakia does not produce the same economic benefit as it may in other countries. However, once we control for country-specific effects in the Fixed Effects model and correct for endogeneity in the 2SLS model, the coefficient for Slovak_DIGI becomes positive and statistically significant at the 1% level in both cases: 0.00222 for Fixed Effects and 0.00222 for 2SLS. Because country fixed effects absorb everything time-invariant, the Slovak coefficient is identified solely from movements over time within Slovakia; it should therefore be interpreted as a within-country growth elasticity rather than as a cross-country premium.

By removing the unobserved heterogeneity and endogeneity from the regression discontinuity approach, digital infrastructure is statistically significant in affecting economic growth in Slovakia. Arguably, the underused digital potentials compared with other countries sampled are indicated in this trend of positive performance of digital infrastructure contribution to growth in Slovakia.

Besides, other important variables like human capital and unemployment are significant in all the models while human capital has consistently been positively related to growth, whereas unemployment is negatively affecting growth, further reinforcing that a high level of unemployment acts as an obstacle to economic growth. While the impact of government expenditure and trade openness varies from model to model, the negative sign of government spending in all the estimated models indicates that more efficient public spending is relevant for stimulating growth.

Results therefore underline the critical role of digital infrastructure for economic growth, especially in the case of Slovakia, where the positive effect of digital infrastructure becomes more pronounced once endogeneity is taken care of. This result calls for focused policies to improve digital infrastructure and its adoption in Slovakia to realize the full growth potential. These findings also reinforce each other and thus reinforce the different econometric specifications, and, as a result, valuable input can be given to policymakers in Slovakia and similar economies.

Table 4. Regional retrogression results of the 2SLS estimate on the productivity growth

	(7)	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	SK	V4	WEU	NEU	SEU	EEU	SEEU
DIGI	0.00840***	0.00854***	0.00323***	0.00461***	0.00390**	0.00973***	0.00792***
	(0.00107)	(0.000660)	(0.000418)	(0.00139)	(0.00188)	(0.000997)	(0.000961)
GFCF	0.00719*	0.00859	-0.00248	-0.00293	0.0109*	0.00855***	0.00998
	(0.00382)	(0.00526)	(0.00602)	(0.00380)	(0.00634)	(0.00317)	(0.00610)
GSE	-0.0127***	0.000219	0.00114*	0.00239***	0.00315	0.00214	7.67e-05
	(0.00417)	(0.00675)	(0.000675)	(0.000766)	(0.00207)	(0.00310)	(0.00118)
GDPG	-0.000773	0.000863	0.00487***	0.00212	-0.000108	0.00272	-0.000155
	(0.00194)	(0.00372)	(0.00134)	(0.00157)	(0.00401)	(0.00210)	(0.00236)
UNEMP	-0.0209***	-0.0172***	-0.00815**	-0.0145**	-0.00654	-0.0137***	-0.0131***
	(0.00334)	(0.00408)	(0.00322)	(0.00618)	(0.00470)	(0.00351)	(0.00452)
TO	-0.000307	-0.00126*	0.000448*	0.00229***	0.00236	-0.00190**	0.000336
	(0.000765)	(0.000648)	(0.000270)	(0.000813)	(0.00169)	(0.000852)	(0.00117)
PG	-0.0735	-0.0694***	-0.00906	0.104***	0.0349	-0.0464***	-0.0164
	(0.0602)	(0.0244)	(0.0153)	(0.0311)	(0.0232)	(0.0159)	(0.0120)
GGFCE	-0.0267***	-0.0173**	-0.00394	-0.0321***	0.00867	-0.00535	0.00841
	(0.00570)	(0.00744)	(0.00887)	(0.00901)	(0.0107)	(0.00864)	(0.0117)

Constant	10.82***	9.397***	10.52***	10.19***	8.834***	8.759***	8.543***
	(0.412)	(0.816)	(0.211)	(0.302)	(0.433)	(0.484)	(0.475)
Observations	34	136	204	238	238	204	136
R-squared	0.987	0.943	0.931	0.907	0.765	0.946	0.927
Number of countries	1	4	6	7	7	6	4
Under identification and weak instrument tests							
Anderson L $\chi 2$ stat	10.98	11.98	25.63	11.53	26.67	22.43	19.97
p-value	0.896	0.098	0.097	0.076	0.0654	0.050	0.087
Cragg-Donald F stat.	8.24	10.44	12.54	12.78	14.54	13.43	11.98

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Source: Author calculations

According to table 10., the subsection extends the analysis through the application of 2SLS by splitting the sample into regional subgroups: Slovakia, V4 countries, Western Europe, Northern Europe, Southern Europe, Eastern Europe, and Southeastern Europe. These are categories which also enable one to carry out a comparative study on how different degrees of digital infrastructure are influencing economic growth across varied contexts in Europe. Controlling for both country and time-specific effects, this captures the effect of digital infrastructure better on productivity because regional variations may be accounted for. Results interpreted within the frame of the econometric model (4); robust standard errors have been applied to present reliable estimates of the parameters being estimated.

Results are presented in table 10., offers an overall comparison of the effects of digital infrastructure on economic growth in different regions: Slovakia, V4 countries, and other EU regions. The main attention will be paid to the impact of digital infrastructure and its differentiated impacts in the case of Slovakia and other regions, with a focus on the relevance of the interaction between digital infrastructure and regional characteristics.

In Slovakia, the coefficient for digital infrastructure is statistically significant at the 1% level (0.00840), indicating that digital infrastructure has a positive and substantial effect on economic growth. This suggests that, in Slovakia, increased digital infrastructure leads to a noticeable improvement in economic performance, which aligns with previous findings indicating that digital infrastructure can drive productivity growth in developing economies. The relatively high coefficient for digital infrastructure in Slovakia compared to other regions emphasizes its potential as a key driver of economic development in the country. Additionally, the high R-squared value of 0.987 for Slovakia suggests a strong explanatory power of the model, indicating that digital infrastructure is a crucial factor in explaining the variation in economic growth within the country.

It is perceived that digital infrastructure has an important role to play in all the regions; however, the strength of this factor varies: for the V4 countries, including Slovakia but also other Central European countries, the respective coefficient stands at 0.00854, slightly higher compared to Slovakia, yet positive and significant for economic growth. The coefficient is comparatively smaller, 0.00323, for the WEU region, which points out a weaker but significant relation between digital infrastructure and growth. That may be explained by the fact that the economies of Western Europe already reached such a high level of digital infrastructure that further digital investments give them relatively lower returns compared with countries that had lower starting positions, like Slovakia.

Other regions, such as Northern and Southern Europe, also have high impacts of digital infrastructure, represented by coefficients 0.00461 and 0.00390, respectively. In contrast with the case of Slovakia and V4 countries, the magnitude of effects is again much lower, presumably because those countries are far more advanced in their economic maturity and technological adoption. The Eastern European and Southeastern European regions show much stronger effects of digital infrastructure, with coefficients of 0.00973 and 0.00792, respectively. This is also in line with the notion that economies in these regions are catching up significantly, where digital infrastructure and technology adoption are still rapidly expanding and more substantially contributing to economic growth.

Most of the other variables display region-specific characteristics of human capital, government expenditure, and trade openness. Government expenditure, for example, is negative for Slovakia with -0.0267, insinuating that there is probably a certain inefficiency in public spending which is dampening growth in the country. This effect is much more heterogeneous for other regions, for instance, Northern Europe, where the overall coefficient is negative, -0.0321 in the Southern EU, reflecting regional heterogeneity in how the level of public spending relates to economic growth.

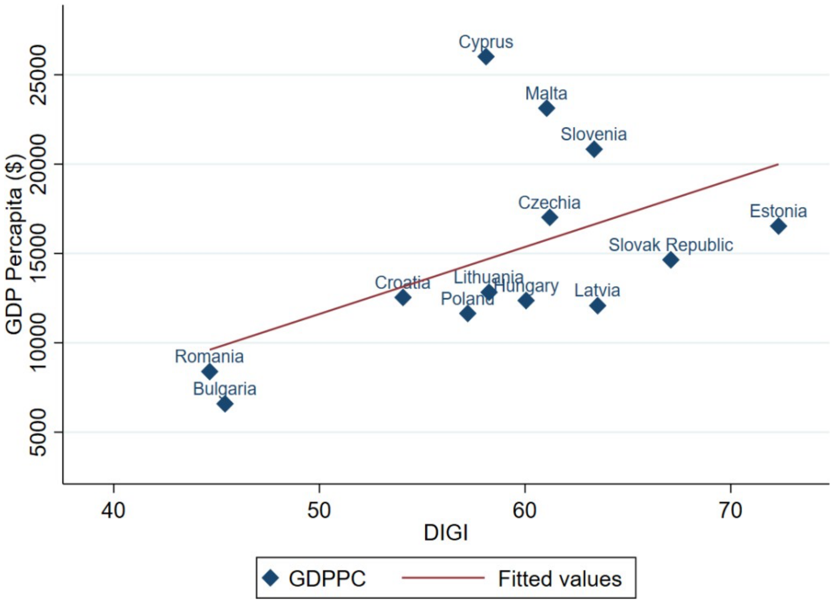
In general, the findings would suggest that at different levels of technological development and in different regional contexts, the role of digital infrastructure is critical in determining regional economic growth. At the same time, Slovakia indicates a relatively higher coefficient of digital infrastructure, indicating that the economy needs to develop a strategic way of pursuing economic growth through digital transformation. The positive and significant coefficients across regions really pinpoint the relevance of focused policies that enforce digital infrastructure, especially in those areas where this still holds enormous potential to contribute to economic growth, such as in eastern and southeastern Europe.

The results thus suggest that digital infrastructure holds immense promise for economic growth in Slovakia. However, the full potential of digital infrastructure can be realized in Slovakia only with structural policies that address several challenges related to government expenditure, human capital, and unemployment. Moreover, ensuring technological innovation and more internet and broadband access will prove very important in terms of sustainability of long-term growth. The continuous prioritization of digital infrastructure provides the opportunity for Slovakia to become a competitive player in the European economy and to drive inclusive growth, narrowing the gap with more technology-advanced regions.

Second part of this research explores to what extend does the diffusion of digital infrastructure causally impact GDP per capita in EU-13 countries, namely Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovak Republic and Slovenia.

Figure 7 presents the scatter plot of digitization versus GDP per capita in the EU13 countries. A fitted line indicates that there is a positive relationship between the two variables. With high DIGI scores over 60% and relatively high GDPPC, Estonia, Slovenia, Malta, and Cyprus emerge as regional digital and economic leaders, while Bulgaria and Romania are on the opposite side, with the lowest DIGI values below 50%, and combining these with the lowest GDPPC, which further strengthens the nexus between limited digital adoption and weaker economic performance. There might be a reason in the structure of their economy why at a middle level of DIGI, Latvia, Poland, and Hungary have a rather lower GDPPC than what might be expected. Additionally, while Cyprus has only average levels of digitization, the country enjoys an exceedingly high GDPPC; therefore, growth must be caused by other economic and institutional reasons. From an econometric perspective, such outliers may bias regression estimates and lead to distorted conclusions about the real impact of digitization on economic performance. Overall, what this graph shows is that where digital adoption is greater, so is prosperity, though such factors as investment, education, and trade openness explain more variance in GDP per capita.

Figure 2. The relationship of GDP per capita and digitization (2000-2023)



Source: author calculation

<u>Variance inflation factor</u>

The VIF values are generally very low, which indicates that multicollinearity is not a problem in this dataset. The variable with highest VIF is DIGI (2.158) which reflects its relatively stronger correlation with other regressors, notably trade openness (TO) and school enrolment (GSE). Variables TO (1.901) and UNEMP (1.447) also exhibit modest multicollinearity, which is not uncommon in macroeconomic models where structural variables may interact. (L.

GDPG) shows one the lowest VIF (1.315). Interestingly, GFCF and GGFCE have the lowest VIF values in the set (1.257 and 1.118) what indicates that their inclusion contributes relatively independent explanatory power. All variables have a 1/VIF greater than 0.5, suggesting that they each explain a reasonable amount of unique variance. With a Mean VIF of 1.498, it is easy to conclude that the variables are independent of each other and hence regression models based on such data are least likely to face severe multicollinearity issues. This is a consistent finding as it is an assurance that interdependencies among the variables can be represented more accurately and not skewed through collinearity.

Table 5. Variance inflation factor

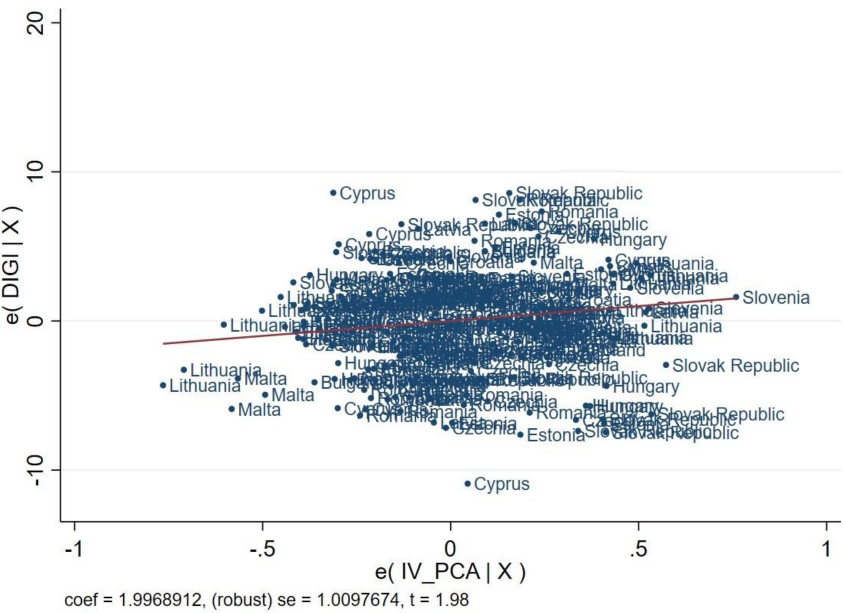
	VIF	1/VIF
DIGI	2.158	.463
TO	1.901	.526
UNEMP	1.447	.691
PG	1.428	.7
GSE	1.363	.734
L.GDPG	1.315	.761
GFCF	1.257	.795
GGFCE	1.118	.894
Mean VIF	1.498	.

Source: author calculation

Regression results

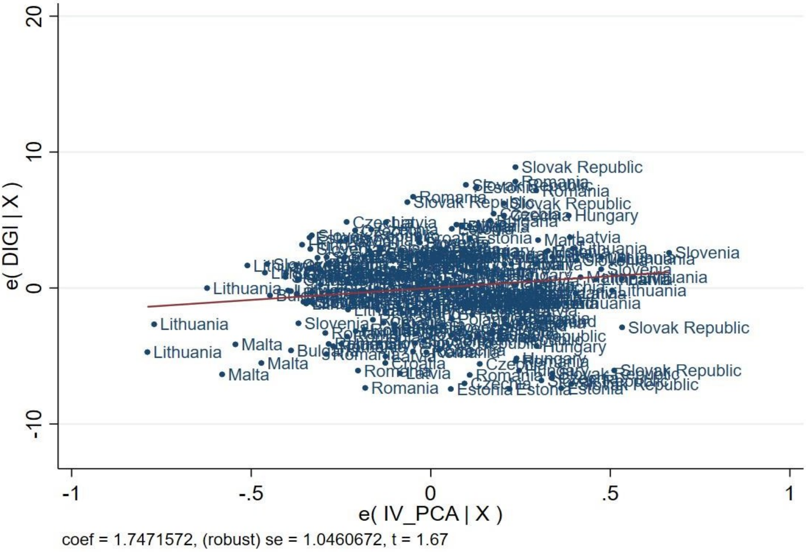
In Figures 8 and 9, the added-variable plots represent the first-stage regression results using the instrumental variable approach, in which digitization is instrumented by the principal component analysis of fixed broadband subscriptions and mobile cellular subscriptions. In both plots, the fitted lines-that are only slightly upward-sloping-represent a weak but positive first-stage relationship. For the full EU13 sample, the coefficient is 1.9969 with a robust standard error of 1.0098 and t-statistic of 1.98 which is statistically significant. Once Cyprus is excluded, the coefficient weakens to 1.7472 with a standard error of 1.0461 and t-statistic of 1.67-a relatively weak instrument. This decline in importance suggests that Cyprus might have played an important role in strengthening the instrument, possibly due to its peculiar digital infrastructure. Besides, several other countries, such as Slovakia, Slovenia, Romania, Latvia, and Lithuania, emerge as partial outliers, reflecting important heterogeneity of digital adoption across the EU13. Considering such results, though the instrument seems relevant, its low correlation with DIGI in the second sample could be questioned. Other diagnostics, such as weak instrument tests, are also applied before strong causal inferences about the impact of digitization on GDP per capita growth can be drawn.

Figure 3. Added variable plot from the first stage retrogression, full sample



Source: author calculation

Figure 4. Added variable plot from the first stage retrogression, sample without Cyprus



Results of analysis depicted in table 15 assesses the effects of digitalization on GDP per capita, according to the fitted OLS and IV (2SLS) regression models on EU13. From the below OLS result in first column of table 15., one finds that DIGI is positively associated with log_GDPPC, having an estimated coefficient equal to 0.0042 and *p*-value of 0.000, while GDPG and UNEMP are negatively affecting it with the coefficients -0.0042 and -0.0183, respectively, and PG was positively related, with the value 0.0246, and p-value of 0.011.

Columns 2 and 3 of table 15 explain the causal effect of changes in digitization to economic growth by using an instrumental variable approach among a sample of 13 EU countries between 2000 and 2023. At first stage, we predict the change in digitization by our instrument, IV_PCA variable, in combination with other control variables. This instrument explains a big part of the variation in the change of digitization. We also conduct some under identification and weak instrument tests, which reassure us that our instrument is strong enough. This takes us to the second step of our estimation, where we present the regression results showing that digitization significantly affects growth. The first-stage regression result gives an IV_PCA coefficient of 1.997, with a *p*-value of 0.049, hence, the relevance of the instrument. In column 3, the effect of DIGI increases to 0.0232 with a *p*-value of 0.030 in the second stage regression, hence, OLS may have underestimated its effect. While GDPG (-0.0076) and UNEMP (-0.0247) stay negative at significance, PG loses significance. Further diagnostic tests confirm the instrument validity, considering the Kleibergen-Paap test with $p = 0.0397$ supporting the IV approach. Finally, digitalization exerts a positive effect on GDP per capita; the result using IV is stronger compared with OLS.

Further, from the sensitivity analysis shown in Figures 8 and 9, it is evident that this effect is actually driven by Cyprus. In order to alleviate this problem, we re-estimate our model excluding Cyprus. Curiously enough, once this outlier is removed, the relationship between digitization and growth strengthens even further. That would mean the significance observed for the full sample initially was driven by outliers rather than a robust effect. Furthermore, the first-stage regression results in column 5 of table 6 suggest that our instrument still explains an essential share of digitization changes and that its strength improves once Cyprus is excluded. However, the Cragg-Donald *F*-statistic remains above 10, which generally suggests a weak instrument bias of about 10 to 15%. Figure 7 plots the relationship between the instrument and digitization changes in the adjusted sample as another way to illustrate this. Finally, the IV regression-robust to outliers-continues to yield a significant effect of changes in digitization on future growth. The above evidence suggests that the original small coefficient in the full sample was primarily an outlier effect. More importantly, our results support the earlier findings by Tranos (2012), Czernich et al. (2011), and Novikova & et al. (2022) because their significant effect of digitization levels on growth using a comparable methodological approach lends great strength to our findings.

Table 15. Regression results

Dep: Log.GDPPC	(1)	(2)	(3)	(4)	(5)	(6)
	Full Sample			Without Cyprus		
	Fixed Effect	IV Estimates		Fixed Effect	IV Estimates	
VARIABLES	OLS	1st Stage	IV	OLS	1st Stage	IV
DIGI	0.00421***		0.0232**	0.00507***		0.0439**
	(0.00113)		(0.0107)	(0.00113)		(0.0219)
L.GDPG	-0.00419**	0.184*	-0.00756**	-0.00218	0.179*	-0.00830
	(0.00169)	(0.0990)	(0.00310)	(0.00164)	(0.101)	(0.00566)
UNEMP	-0.0183***	0.325**	-0.0247***	-0.0126***	0.371**	-0.0253***
	(0.00185)	(0.128)	(0.00449)	(0.00210)	(0.155)	(0.00980)
GGFCE	-0.0159***	-0.977***	0.00360	-0.0181***	-0.921***	0.0167
	(0.00548)	(0.294)	(0.0127)	(0.00517)	(0.301)	(0.0242)
GFCF	0.00323	-0.114	0.00449	0.00416**	-0.0564	0.00461
	(0.00197)	(0.138)	(0.00333)	(0.00195)	(0.142)	(0.00578)
GSE	-0.00153	-0.169*	0.00191	-0.00112	-0.219***	0.00724
	(0.000990)	(0.0861)	(0.00264)	(0.000942)	(0.0839)	(0.00579)
TO	-2.26e-05	0.0462	-0.00115	7.90e-05	-0.0185	0.000338
	(0.000410)	(0.0281)	(0.000813)	(0.000424)	(0.0291)	(0.00106)
PG	0.0246**	-0.892*	0.0506***	0.0163*	-0.676	0.0491*
	(0.00964)	(0.497)	(0.0146)	(0.00896)	(0.537)	(0.0259)
IV_PCA		1.997**			1.747*	
		(1.010)			(1.046)	
Constant	9.040***	31.68***	8.543***	8.907***	37.80***	7.714***
	(0.187)	(11.73)	(0.397)	(0.175)	(11.76)	(0.836)
Observations	284	277	277	262	256	256
R-squared	0.984	0.971	0.954	0.984	0.973	0.853
Number of countries	13	13	13	12	12	12
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Under identification and weak instrument tests		***Statistic***	***p-value***		***Statistic***	***p-value***
Kleibergen-Paap Under identification Test		4.23	0.0397		3.04	0.0514
Cragg-Donald Wald F Statistic		13.83			11.53	
Anderson-Rubin Wald Test		10.20	0.0016		32.58	0.0000
Stock-Wright LM S Statistic		14.85	0.0001		39.28	0.0000

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: author calculation

To strengthen the validity of the findings, the 2SLS analysis is complemented with additional regressions using broader measures of digital infrastructure, such as DESI-Connectivity, internet speed, and cybersecurity. These indicators are tested for robustness in the second-stage regression and produce consistent results. Further, classical OLS and Fixed Effects models are reported in Table 9 as comparison benchmarks to validate the consistency of the causal claim. The initial use of fixed broadband and mobile cellular subscriptions as core instrumental variables is grounded in their strong and direct relationship with internet accessibility, closely following validated approaches by Gruber et al. (2014). However, acknowledging the limitation raised regarding the narrower scope of these indicators, this research explicitly incorporates additional robustness checks using broader measures reflecting different digital infrastructure dimensions, specifically connectivity quality (DESI-Connectivity), internet speed (Ookla Speed test Index), and digital security (ITU Cyber-Security Index). These analyses confirm that the results remain stable and robust across multiple dimensions of digital infrastructure.

Table 16. Robustness checks of digital infrastructure indicators (2014–2023)

Indicator	First-stage F	Elasticity (GDP per capita)	Hansen J (p-value)
DESI-Connectivity	12.6	0.024 (0.010)**	0.254
Median download speed	11.4	0.026 (0.012)**	0.302
ITU Cyber-Security Index	18.3	0.019 (0.009)**	0.184

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

6. Conclusion

This dissertation thesis investigated the role of digitization in driving economic growth, with a particular focus on Slovakia and its comparative position within the EU-27, and 13 Central and Eastern European countries. The findings underscore the significant positive impact of digitization on economic growth across all regions, though the magnitude of this effect varies depending on the level of technological development and regional context. Analysis for Slovakia shows more powerful and stronger significance of relationship between digitization and economic growth with coefficient even higher than in more technologically advanced regions such as western and northern Europe. This implies that expanding the coverage of digital infrastructure in the form of fixed broadband and mobile cellular networks should lead to large benefits for an economy like Slovakia. The study highlights some challenges (inefficiencies in government spending and levels of human capital development) that are likely to limit the extent to which the gains from digitization can be attained. Further, the cross-sectional comparison is used to show that digitization has a positive impact on growth across the EU regions, but the effect is stronger in less-developed regions, which are in catching-up phase of digital adoption. This is consistent with the general discussion in the literature that digital technologies have the potential to transform how wealth is created and is shared for more inclusive growth. To seize these advantages, policymakers in Slovakia and corresponding countries need to focus on strategic measures, including investment in broadband, strengthening digital skills, and getting the most from public money. Thus, promoting innovation and maintaining access on fair terms to digital tools to drive sustainable growth and competitive advantage in the future will be essential for EU economies.

On the CEE, empirical analysis demonstrates that there is strong evidence of a causal association between digital infrastructure and the growth in GDP per capita, and that this relationship is conditioned by human capital development and territorial digital maturity. Such outcomes present important implications for policymakers who seek to harness the digital technologies as a mechanism of economic development and emphasize that comprehensive strategies ought to integrate infrastructure investments with human education and vocational development. The research also draws attention to persistent challenges, above all the urban-rural digital divide and uneven up-take in CEE countries. Whereas Estonia and Malta have emerged as the digital frontrunners, Bulgaria and Romania lag, and thus targeted interventions may at times be required to drive more balanced growth. The study's methodological innovations, particularly its use of instrumental variables to deal with endogeneity, provide a solid platform on which subsequent research in this area can be conducted. Forward looking, as CEE economies continue with their digital revolutions, several priority issues emerge. First, further investments in next generation infrastructure will be necessary to remain competitive in an increasingly digital global economy. Second, digital literacy and skills policies need to keep pace with technological advancements to allow workers to respond to changing labor market demands. Third, global cooperation, and particular in the EU context will have a key function to play in promoting digital convergence in the region. Overall, this research reaffirms that digital infrastructure is not only an enabler but a major driver of economic transformation in the 21st century. For CEE countries, the full potential of digitization will be realized through sustained, collective efforts across a variety of policy domains, a challenge that, if met, can propel the region toward more sustainable and inclusive growth in the coming decades. The findings suggest that if digital development is pursued comprehensively in terms of innovation, skills, and infrastructure, it will be a powerful engine for economic convergence and improved standards of living in the region.

This research acknowledges limitations related to omitted institutional reforms, macroeconomic shifts, and country-specific shocks, especially in early accession years for CEE countries. Although the IV approach mitigates endogeneity, unobserved factors might still influence the GDP-digitalisation link. The findings should therefore be interpreted as strong evidence of a causal association but not as an absolute quantification of long-run digital policy effects. The model does not explicitly estimate time-lagged effects or dynamic adjustment paths, which may vary across regions. Future research could apply dynamic panel models (e.g., System-GMM) to capture delayed effects of infrastructure investment. Moreover, regional heterogeneity in broadband rollout, digital skills, and institutional readiness should be studied more granularly using subnational data or region-by-time interactions.

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9. Summary

The increasing speed of digitization has transformed the global economy, reshaped industrial sectors, improved productivity, and redefined competitive advantages. In this process, digital infrastructure has become one of the key drivers of economic growth. Central and Eastern European (CEE) countries, as well as advanced EU countries, represent an interesting sample for studying this relationship. These countries have experienced widespread adoption of digital technologies, but disparities in broadband access and connectivity persist among them. Research into the impact of digital infrastructure on the economic growth of CEE countries, Slovakia, and the EU-27 offers important insights into how such investments can stimulate economic development and improve productivity. The expansion of broadband, mobile, and cloud environments has accelerated information exchange, thereby increasing productivity in sectors such as finance, manufacturing, and services.

Empirical evidence confirms that broadband penetration plays a key role in supporting economic growth. Alam et al. (2019) demonstrated that access to broadband internet boosts GDP growth through improved information flows, business operations, and consumer participation. These findings are in line with the economic profile of EU-13 countries, where improved access to digital technologies can positively influence the business environment and attract foreign direct investment (Alam et al., 2019).

The impact of information and communication technologies (ICT) on economic performance is well-researched in developing regions. Bahrini and Qaffas (2019) identified a strong relationship between ICT adoption and GDP growth in the Middle East, North Africa, and Sub-Saharan Africa. Their study found that mobile telecommunications and internet access stimulate economic participation, particularly in underserved communities.

Myovella et al. (2020) emphasize that the impacts of digitization on economic performance tend to differ depending on the level of regional development. Their study showed that digital connectivity significantly accelerated economic growth in OECD economies, while mobile telecommunications services had a much greater impact in developing countries. However, despite extensive research on the connection between digitization and economic growth, significant gaps remain in understanding how digital infrastructure affects different economies — such as the EU-13 region.

Previous studies have identified broadband access as a growth-promoting factor, but evidence on long-term causality and the mechanisms of this impact is limited for EU-13 countries (Tranos, 2012; Czernich et al., 2011). Moreover, concerns about endogeneity persist, raising questions as to whether economic growth leads to digital investments, or vice versa (Brynjolfsson & McAfee, 2014). Addressing these questions requires the use of robust econometric techniques capable of isolating the true causal effect of digitization.

The main objective of this dissertation is to examine the impact of digital infrastructure on Slovakia's economic growth, compare it with EU-27 countries, and determine how digital infrastructure affects GDP per capita in EU-13 countries.

This dissertation uses an extended two-stage least squares (2SLS) method with instrumental variables for panel data to address the issue of endogeneity. The data used come from the WDI, Eurostat, ITU, OECD, and ILO databases.

Key findings include evidence of a significant impact of digitization on economic growth in all observed regions, although the magnitude of this effect differs depending on the level of technological development and regional context. The analysis for Slovakia indicates a stronger and more significant relationship between digitization and economic growth, with a coefficient even higher than in more technologically advanced regions (Western and Northern Europe). This means that expanding digital infrastructure coverage in the form of broadband access and mobile networks should lead to substantial benefits for an economy like Slovakia. Our research emphasizes that certain challenges, such as inefficiencies in government spending and the level of human capital development, may limit the extent to which the benefits of digitization can be achieved.

10. Extended abstract in the Slovak language

Narastajúca rýchlosť digitalizácie zmenila globálnu ekonomiku, transformovala priemyselné odvetvia, zlepšila produktivitu a nanovo definovala konkurenčné výhody. Digitálna infraštruktúra sa v tomto procese stala jedným z kľúčových motorov ekonomického rastu. Krajiny strednej a východnej Európy (CEE) ako aj vyspelé krajiny EÚ predstavujú zaujímavú vzorku na skúmanie tohto vzťahu. Tieto krajiny zažili rozsiahle prijatie digitálnych technológií, no zároveň medzi nimi pretrvávajú rozdiely v prístupe k širokopásmovému internetu a v miere konektivity. Výskum o vplyve digitálnej infraštruktúry na ekonomický rast krajín CEE, Slovenska a EÚ 27 prináša dôležité poznatky o tom, ako takéto investície môžu stimulovať ekonomický rozvoj a zlepšiť produktivitu. Rozširovanie širokopásmového, mobilného a cloudového prostredia urýchlilo výmenu informácií, čím sa zvýšila produktivita v oblastiach, akými sú financie, výroba a služby. Empirické dôkazy potvrdzujú, že penetrácia širokopásmového internetu zohráva kľúčovú úlohu pri podpore ekonomického rastu. Alam a kol. (2019) preukázali, že prístup k širokopásmovému internetu zvyšuje rast HDP prostredníctvom zlepšených tokov informácií, obchodných operácií a účasti spotrebiteľov. Tieto zistenia sú v súlade s ekonomickým profilom krajín EÚ 13, kde zlepšený prístup k digitálnym technológiám môže pozitívne ovplyvniť podnikateľské prostredie a podporiť priame zahraničné investície (Alam a kol., 2019). Vplyv informačno-komunikačných technológií na ekonomickú výkonnosť je v rozvojových regiónoch dobre skúmaný. Bahrini a Qaffas (2019) identifikovali silný vzťah medzi adopciou IKT a rastom HDP na Strednom východe, v severnej Afrike a v subsaharskej Afrike. Ich štúdia zistila, že mobilná telekomunikácia a prístup na internet stimulujú ekonomickú participáciu, najmä v zanedbávaných komunitách. Myovella a kol. (2020) zdôrazňujú, že dopady digitalizácie majú tendenciu líšiť sa pri hospodárskom výkone v závislosti od úrovne regionálneho rozvoja. Ich štúdia ukázala, že digitálna konektivita výrazne urýchlila hospodársky rast v ekonomikách OECD, zatiaľ čo mobilné telekomunikačné služby mali ďaleko väčší dopad v rozvojových krajinách. Avšak, aj napriek rozsiahlemu výskumu o súvislosti medzi digitalizáciou a hospodárskym rastom, pretrvávajú výrazné medzery v pochopení ako digitálna infraštruktúra ovplyvňuje rôzne ekonomiky, napríklad región EÚ 13.

Predchádzajúce štúdie identifikovali širokopásmové pripojenie ako faktor podporujúci rast, ale dôkazy o dlhodobej kauzalite a mechanizmoch tohto vplyvu sú v krajinách EÚ 13 obmedzené (Tranos, 2012; Czernich a kol., 2011). Navyše, pretrvávajú obavy z endogenity, čo vyvoláva otázky, či ekonomický rast vedie k digitálnym investíciám, alebo naopak (Brynjolfsson & McAfee, 2014). Riešenie týchto otázok si vyžaduje použitie robustných ekonometrických techník, schopných izolovať skutočný kauzálny účinok digitalizácie.

Hlavným cieľom tejto dizertačnej práce je preskúmať vplyv digitálnej infraštruktúry na ekonomický rast Slovenska, porovnať ho s krajinami EÚ-27 a zistiť, ako digitálna infraštruktúra ovplyvňuje HDP na obyvateľa v krajinách EÚ-13.

V dizertačnej práci využívame rozšírenú dvojstupňovú metódu najmenších štvorcov s inštrumentálnymi premennými pre panelové dáta na riešenie otázky endogenity. Použité dáta pochádzajú z databáz WDI, Eurostatu, ITU, OECD a ILO.

Medzi kľúčové zistenia patrí preukázanie významného vplyvu digitalizácie na ekonomický rast vo všetkých sledovaných regiónoch, hoci rozsah tohto efektu sa líši v závislosti od úrovne technologického rozvoja a regionálneho kontextu. Analýza pre Slovensko poukazuje na silnejší a významnejší vzťah medzi digitalizáciou a ekonomickým rastom s koeficientom ešte vyšším ako v technologicky vyspelejších regiónoch (západná a severná Európa). To znamená, že rozšírenie pokrytia digitálnej infraštruktúry vo forme širokopásmového pripojenia a mobilných sietí by malo viesť k rozsiahlym výhodám pre ekonomiku akou je Slovensko. Náš výskum zdôrazňuje, že niektoré výzvy, ako neefektívnosť vládnych výdavkov a úroveň rozvoja ľudského kapitálu, môžu obmedziť rozsah, v akom možno dosiahnuť výhody z digitalizácie.