Technological capabilities and economic growth in Visegrad countries

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The Visegrad (V4) countries experienced rapid economic growth from the mid-1990s until the 2008 global financial crisis. While growth resumed after the crisis, its pace has not been strong enough to achieve convergence with advanced economies. This study examines the impact of technological capabilities on economic growth in V4 countries. First, the evolution of two technological capabilities – implementation and design capabilities – is analysed. Subsequently, their impact on economic growth is assessed. The Toda–Yamamoto causality test results indicate that the accumulation of implementation capability (IC) precedes the development of design capability (DC). Panel quantile regression estimates show that implementation capability drives economic growth at lower income levels, while design capability becomes more influential at higher income levels. Foreign direct investment (FDI)-led growth in V4 countries primarily relies on implementation capability, but this model has reached its limits. At this stage of development, design capability is crucial for catching up with advanced economies by fostering new technologies and business models on a global scale. Therefore, governments should recognize this economic shift and implement measures to strengthen design capability.

Keywords:
technology,
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Introduction

Amid deep institutional reforms and integration into the European Union (EU), foreign direct investment (FDI)-led modernization spurred rapid economic growth in four Visegrad (V4) countries from the mid-90s until the 2008 crisis (Farkas 2020).

However, the FDI-led development path, which was based on cost and efficiency competitiveness, has reached its limits in driving economic development in these countries (Szalavetz 2017). At this stage of development, introducing new products with unique functions and specifications is necessary for continued advancement and for joining the ranks of advanced economies. The ability to produce novel products and services globally necessitates accumulating respective technological capabilities (Fagerberg–Srholec 2021). The literature on the economic growth–technology nexus claims that different technological capabilities are required at various stages of economic development (Lall 1992, Kim 1997). This study aims to evaluate economic growth in V4 countries concerning different types of technological capabilities.

Lee et al. (2019) identify two types of technological capabilities: implementation and design. Implementation capability enables efficient production within the constraints of existing technology and is essential at lower and middle levels of national income. Conversely, design capability refers to the ability to introduce new products, technologies, and business models with unique specificities, making it crucial for transitioning from a middle-income level to an advanced economy. Following the methodological approach of Lee et al. (2019), this study investigates the evolutionary shift from implementation to design capability. It evaluates the impact of two technological capabilities on economic growth at different national income levels in V4 economies. Specifically, it investigates whether accumulating implementation capability is necessary for developing design capability in these countries and whether the two capabilities have distinct effects on economic growth at lower and higher income levels. The causality test results support the hypothesis that implementation capability contributes to this region's design capability accumulation. Additionally, regression model results confirm that the effect of implementation capability on economic growth diminishes as income levels rise. Conversely, the influence of design capability strengthens with increasing GDP per capita.

There are few studies investigating the importance of different technological capabilities in helping Central Eastern European (CEE) countries catch up with advanced economies (Radosevic–Yoruk 2016, Radosevic et al. 2019), and none mainly focused on V4 countries. Existing studies primarily evaluate the innovativeness of V4 countries and regional disparities in innovation using general indicators from the global innovation index (Walasik et al. 2024). This study contributes to the literature on the technology–economic growth nexus in the CEE region.

The study is organized as follows: first, essential literature on the technology–growth relationship is reviewed, and a theoretical explanation of implementation and design capabilities is provided. The author presents the empirical measurement of these two technological capabilities. Then, the econometric model of analysis is introduced. Finally, the results are discussed, and the policy recommendations are concluded.

Theoretical background

Schumpeter (1934) recognized the decisive role of technological advancement in economic development. Following Solow (1956), academic interest in quantifying the effects of technology on economic growth increased. Since the 1980s, growth models have been developed to link endogenous technological change to economic growth. Unlike the Solow model, where technology is treated as homogeneous and exogenous, endogenous growth models consider technological development as an internal process. Lucas (1988) emphasizes the role of human capital in spurring technological change and driving long-run growth. Accordingly, investment in human capital by individuals and governments fuels productivity growth. Romer (1990) argues that technological change is not exogenous but driven by intentional investment made by profit-maximizing firms. In Romer's endogenous growth model, firms operating in monopolistic competition allocate resources to research and development to create new products and technologies. This innovation grants them temporary monopoly power, incentivizing further advancements. Building on Schumpeter's idea of creative destruction, Aghion–Howitt (1992) propose that innovation continuously replaces older technologies with more productive ones, making creative destruction the key driver of long-run economic growth. Introducing new products and technologies promises profits, motivating firms to invest in innovation. Consequently, firms' profit-making decisions shape technological progress, which is not determined exogenously. Unlike the Solow model, which emphasizes the role of physical capital in economic development, endogenous growth models focus on technological progress as the primary driver of sustained economic growth.

The Solow-model predicts that poor countries will grow faster than rich countries due to diminishing returns. However, endogenous growth models argue that the convergence of poor and rich countries is unlikely if a technological gap emerges. Empirical studies on economic convergence also emphasize that human capital accumulation and the production of technological knowledge are essential for economic catch-up (Sala-i Martin 1996, Islam 2003).

Solow (1957) assumes that technology is an exogenous factor freely available to economic subjects and does not consider the *implications of technology* in a multi-country world. However, other studies recognize that technologies are not freely available and do not diffuse easily across countries (Abramovitz 1986, Fagerberg 1994). Economic development in emerging economies occurs through technological catch-up with advanced economies by continuously upgrading their technologies. This requires adapting, absorbing, upgrading, and commercializing existing and new technologies, collectively known as technological capabilities (Kim–Nelson 2000, Juhász et al. 2024). Depending on their stage of economic development, countries possess and require different technological capabilities (Bell–Pavitt 1992, Lall 2000, Lee et al. 2021).

Kim (1997) identifies three technological capabilities: production, investment, and innovation. Countries can climb the ladder of economic development by enhancing these technological capabilities. Acquiring the full range of innovation capabilities is crucial for reaching the technological frontier and achieving advanced economic status. Production capabilities are essential for operating and maintaining production facilities, ensuring efficiency within the limits of existing technology. Investment capability refers to expanding existing production facilities and establishing new ones. Innovation capabilities involve creating new technologies and upgrading existing ones beyond the original design parameters. Bell–Pavitt (1992) categorize capabilities into *production* and *technological* capabilities. *Production capabilities* encompass the resources required to produce a given level of efficiency and input combinations, including operational and managerial skills and technology embodied in capital. In contrast, technological capabilities encompass resources needed to manage and implement technical changes, such as knowledge, skills, experience, and institutional infrastructure. Similarly, Lall (2000) distinguishes the *know-how* and *know-why* technologies. *Know-how* refers to practical knowledge for operating production facilities and achieving operational capability, whereas *know-why* entails a deeper understanding of technological principles, which is vital for innovation. As technology matures in developing countries, innovation capability becomes increasingly important, necessitating a shift to *know-why* from *know-how*.

Radosevic–Yoruk (2018) introduce the three dimensions of technological upgrading: intensity of technology upgrading, breadth of technology upgrading, and interaction with the global economy. Regarding the intensity of technology upgrading, they propose production, technology capability, research and development (R&D), and knowledge intensity. *Production capability* is the ability to produce world-class productivity and efficiency. The technological capability involves improving existing products and processes. R&D and knowledge intensities are advanced levels of technological upgrading, focusing on developing and introducing new global products and processes.

Lee et al. (2021) explain the middle-income trap through two distinct technological capabilities. *Concept design capability* (hereafter *design capability* [DC]) involves the skills to generate blueprints, business frameworks, and benchmarks for new products and services. *Implementation capability* (IC) refers to the ability to produce within a given design and enhance efficiency through experience (Yeon et al. 2021, Lee et al. 2021). This classification aligns with distinctions in the literature, such as production and innovation capabilities by Kim (1997), production and technological capabilities by Bell–Pavitt (1992), and *know-how* and *know-why* capabilities by Lall (2000). *At the lower level of technological development, implementation capability drives technological accumulation. As implementation capability grows substantially, design capability begins to take the lead in technological development.* Lee et al.'s (2021) approach is distinctive in its focus on various types of technological knowledge, different forms of technological learning, and diverse targets of technological activities. The following subsection discusses the characteristics of design and implementation capabilities in greater detail.

The characteristics of implementation and design capabilities

The expression of technological capabilities ranges from absorbing existing technologies to developing new ones. According to Lee et al. (2021), introducing products and services necessitates design capability, which defines their functions and specifications, and implementation capability, which ensures their physical realization. This section presents the study's conceptual framework, distinguishing between these capabilities. The framework is based on a synthesis of *knowledge management* and *organizational learning* literature.

Knowledge management literature differentiates between tacit and explicit knowledge in production processes (Polanyi 1958, Collins 2019). Tacit knowledge is gained through experience and is difficult, if not impossible, to express and transfer to others. In contrast, explicit knowledge can be easily described, codified, and shared (Polanyi 1966). Successful knowledge creation and innovation within an organization require understanding how tacit knowledge is converted into explicit knowledge, which stimulates the *creation* of new tacit knowledge (Nonaka 1994). Nonaka–Takeuchi (1995) describe organizational knowledge creation through four modes of knowledge conversion: *socialization*, *externalization*, *combination,* and *internalization*. *Socialization* involves transferring tacit knowledge through direct interaction, where language plays a minimal role; experience is paramount. *Combination* creates new explicit knowledge by editing, sorting, combining, adding, and reconceptualizing existing explicit knowledge. *Externalization* converts tacit knowledge into explicit knowledge, while *internationalization* converts explicit knowledge into tacit knowledge. This model of organizational knowledge creation provides insights into technological capabilities at the national level. Specifically, the evolution from socialization to combination aligns with the ability to share tacit knowledge and *create* new technologies. The transition from combination to internalization reflects the ability to apply explicit knowledge and implement existing technologies.

The organizational learning literature primarily focuses on exploiting existing certainties and exploring new opportunities (March 1991, Katila–Ahuja 2002, Zollo–Winter 2002). March (1991) identifies experimentation, variation, discovery, and innovation as exploration activities, while choice, efficiency, production, refinement, and implementation are categorized as exploitation activities. If a firm concentrates solely on exploration while neglecting exploitation, it may generate numerous underdeveloped ideas but lack the competence to implement them. Conversely, if a firm prioritizes only exploitation without exploration, it risks becoming trapped in *suboptimal stable equilibria.* Therefore, balancing exploitation and exploration is essential for a firm's survival and growth. Katila–Ahuja (2002) reinterpret exploitation and exploration through the concepts of search depth and search scope. Search depth refers to using and reusing existing knowledge, while search scope involves creating new knowledge. They extend the traditional unidimensional understanding of exploration versus exploitation into a two-dimensional concept. The second dimension they introduce emphasizes the intensity of using both old and new knowledge, focusing on using existing knowledge. A substantial amount of exploitation is essential for improving efficiency, mastering existing technologies, and ultimately fostering new knowledge creation. Based on organizational learning literature, the successful combination and organization of exploiting old certainties and exploring new possibilities determine successful innovation.

Table 1 illustrates implementation and design capabilities by integrating knowledge management and organizational learning literature into the technological capability framework. As previously defined, implementation capability refers to actualizing a given technology. This capability primarily relies on explicit knowledge like manuals, which facilitates easier transfer (Cowan et al. 2000). The main performance criterion is efficiency in terms of speed and cost. The primary strategy for improving efficiency involves learning by doing through the execution of technology and exploitation search activities. The availability of technology reduces the difficulty and cost associated with acquiring implementation capabilities.

Tacit knowledge, derived from individuals' experiences and technologies embedded in the organizational environment, is central to the design capability required for introducing *novel* concept designs. The performance of design capability is measured by uniqueness and differentiation, aligning with the objectives of exploration activities. Accumulating experience through trial and error is essential for opening new paths by introducing innovative concept designs. This experience is accumulated through learning-by-building activities like variation, experimentation, and discovery. Additionally, acquiring design capability is often complex and costly.

Table 1

Main characteristics of implementation and design capabilities

Key aspects	Implementation capability (IC)	Design capability (DC)
modes of expression	explicit	tacit
performance criteria	efficiency	differentiation
strategy to nurture	learning by doing with the accumulation of repetitive execution	learning-by-building with the accumulation of trial and error
time and cost of learning	low to medium	medium to high

Source: Lee et al. (2019).

Measuring two technological capabilities

This section quantifies the theoretical concepts of implementation and design capabilities using a composite index that captures the multifaced aspects of technological capabilities. Five indicators are constructed to measure these capabilities, considering different types of knowledge and learning models. For implementation capabilities, the type of knowledge reflects the ability to manage and secure the information needed to actualize an existing design. In contrast, design capabilities focus on creating a differentiated design from existing ones. Regarding learning models, repeated practice in the production process (learning by doing) is central to adapting and assimilating technological knowledge for implementation capabilities. Conversely, the learning process for design capabilities occurs through trial and error (learning by building), fostering the creation of new technological knowledge to develop innovative designs.

The implementation and design capabilities components are based on Lee et al.'s (2019) approach (Table 2). The ISO 9001 certifications and trademark applications by residents represent the type of knowledge associated with implementation capabilities. These indicators reflect the *know-how* knowledge required for the consistent operation of production sites and provision of goods services that meet regulatory and customer quality standards. The ISO 9001 certification is a globally accepted standard for quality management, verifying that an organization can offer goods and services at international standards. Therefore, it serves as a guarantee of operational efficiency (Radosevic–Yoruk 2018). It is also a requirement for public procurement and operations within global value chains (Kaplinsky 2010). In contrast, trademarks signify a certain level of quality with independent brands but do not represent technology at the global technology frontier (Lee et al. 2019). The learning mode for implementation capabilities is represented by three indicators: employment in manufacturing, manufacturing value added per capita, and gross fixed capital formation in the manufacturing sectors. These serve as proxies for routine execution at production sites to implement designs. Additionally, they demonstrate the extent of acquiring disembodied knowledge through learning by doing at production sites (Lundvall–Johnson 1994, Lall 2000, Lee–Baek 2012, Cantore et al. 2017).

Patent and industrial design applications are proxy indicators of the knowledge associated with design capabilities. These indicators represent the ability to comprehend technological principles and introduce new parameters and specific functions (Furman et al. 2002, Kang et al. 2015, Radosevic–Yoruk 2018). R&D (% of GDP) and R&D personnel capture the learning mode of design capabilities, emphasizing trial and error as a form of learning-by-building (Dutta et al. 2016, Filippetti–Peyrache 2011). High-tech exports per capita indicate the ability of commercial trials to introduce and expand novel technologies in the global market (Eichengreen et al. 2013).

Table 2

Components of implementation and design capabilities

National technological capabilities	
implementation capabilities	design capabilities
ISO 9001 certificates (ISO 9001)	patent applications (PATENT)
trademark applications (TRADEMARK)	industrial design applications (INDSTR_DESIGN)
manufacturing value added per capita (MANF_VALUE)	high-tech exports per capita (HIGH-TECH_EXPRT)
employment in the manufacturing sector (MANF_EMPL)	researchers in R&D sector (R&D_PERSONNEL)
GFCF in the manufacturing sector (GFCG_MANF)	R&D spending (R&D_SPENDING)

Source: Lee et al. (2019).

Evaluation of implementation and design capabilities

The data for 10 indicators were collected from 1995–2022 for V4 countries (see in Appendix Table A1 and Table A2). The composite indexes for the two technological capabilities were calculated through normalization (Singh–Singh 2020). The max absolute scaling method was used to rescale all indicators. Initially, this method rescales data into values between −1 and 1. However, since none of the indicators in this study have negative values, the data were rescaled into a range between 0 and 1. The primary strengths of the max absolute scaling method are its ability to preserve the relative distances between data points and its robustness against outliers (Lines–Bagnall 2014, Lima–Souza 2023, Mazziotta–Pareto 2021). The following formula describes the chosen normalization method:

$$\dot{X}_{i,t} = \frac{x_{i,t}}{x_{max}} \tag{1}$$

where $x_{i,t}$ indicates each sub-indicator for country i and year t, while x_{max} indicates the maximum values in each sub-indicator series. $\dot{X}_{i,t}$ indicates the normalized values of 10 sub-indicators, and Table A3 (see in Appendix) presents their descriptive statistics. Two composite indexes, implementation ($IC_{i,t}$) and design ($DC_{i,t}$) capabilities, are computed as the equally weighted sum of five normalized sub-indicator values. The following formula describes national technological capability (NTC).

$$NTC_{i,t} = IC_{i,t} + DC_{i,t}$$

The possible values of $IC_{i,t}$ and $DC_{i,t}$ range from 0 to 5, while $NTC_{i,}$ ranges from 0 to 10.

Cronbach's alpha and composite reliability tests assessed the internal consistency and reliability of the five sub-indicators used in the composite capability indexes. The results indicate that alpha and reliability scores are close to 1 for both capabilities (see in Appendix Table A4). Therefore, each capability's composite indicators can be considered internally consistent and reliable (Wadkar et al. 2016).

Dynamics of implementation and design capabilities

Table 3 indicates that all V4 countries experienced a rise in implementation capabilities. A detailed presentation of the dynamics of sub-indicators of implementation capabilities shows that ISO 9001 follows a positive trend from 1995 to 2022. However, this sub-indicator shifts to a lower state in Hungary in the late 2000s. Overall, IS0 9001 certificates have been a key driver of the rise in implementation capabilities, except in Hungary. Trademarks show a positive trend only in Poland. In the other V4 countries, trademark levels remain stable despite fluctuations, with a slight decline observed in Slovakia. Therefore, trademarks do not contribute to the positive trend in implementation capabilities, except in Poland. Manufacturing employment remains stable, while investment in manufacturing (GFCF) and value-added in the manufacturing sector exhibit strong positive trends across all countries. This suggests that the manufacturing industry is essential in accumulating implementation capabilities in V4 countries.

Table 3

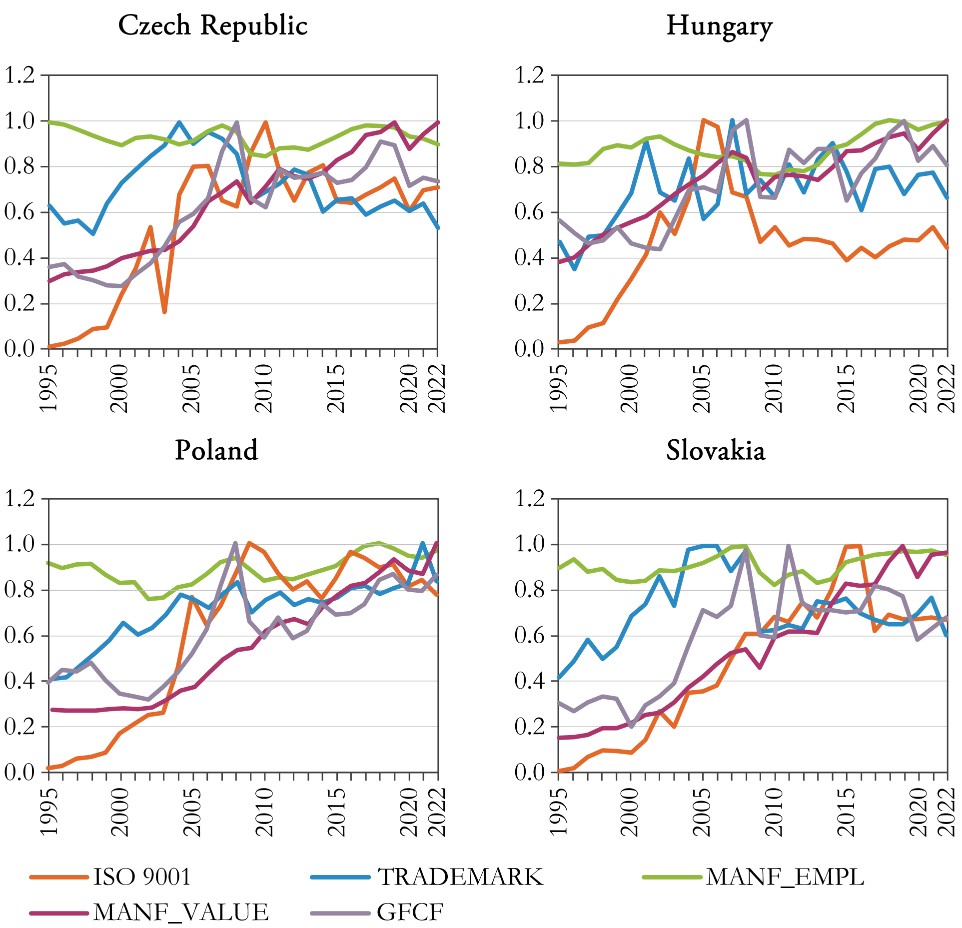
Dynamics of implementation and design capabilities

Country	Capability	1995–2000	2001–2005	2006–2010	2011–2015	2015–2022
Czech Republic	IC	2.26	3.00	3.96	3.91	3.97
	DC	1.81	1.96	2.67	3.70	4.05
Hungary	IC	2.35	3.28	3.89	3.63	3.89
	DC	1.56	2.19	2.24	2.53	2.85
Poland	IC	2.10	2.37	3.63	3.74	4.17
	DC	1.40	1.88	2.24	3.14	4.17
Slovakia	IC	1.97	2.82	3.56	3.83	4.00
	DC	3.09	2.69	2.72	3.70	4.04

Design capabilities are on the rise in these countries. However, the effect of patents on their evolution is not homogenous. In Poland, patents have a positive impact, while in Hungary, the trend is negative. In the Czech Republic and Slovakia, the effect remains stable. Therefore, patents cannot be considered essential in driving design capabilities across region. Industrial design only follows a positive trend in Poland, whereas the trend is negative in Hungary. It shows stability in the Czech Republic and Slovakia. Alternatively, high-tech exports exhibit a positive trend in all countries, primarily driven by the trade specialization of V4 region within the EU. Additionally, R&D spending and R&D personnel have a positive trend across all countries, though Slovakia exhibits only a weak upward tendency.

Figure 1

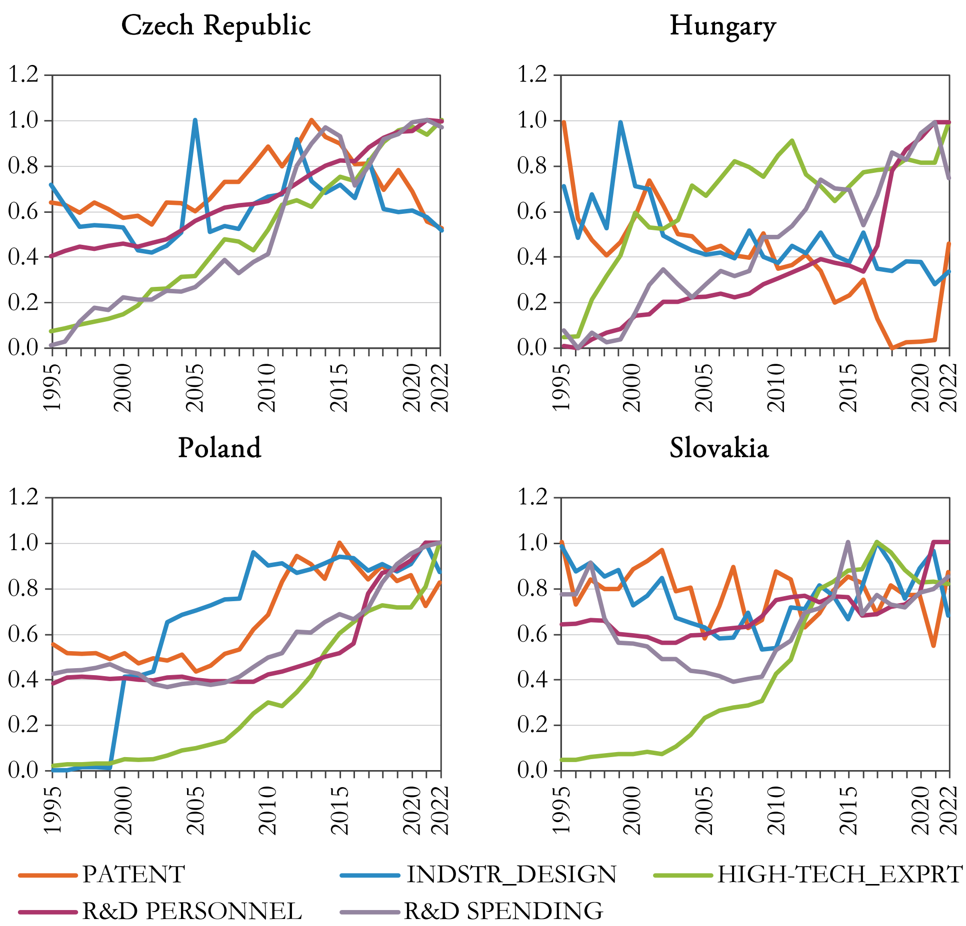
Dynamics of components of implementation capabilities



The dynamics of sub-indicators of design capabilities in V4 countries reveal that macrolevel determinants like R&D and high-tech exports are the primary drivers of progress in this area. Meanwhile, firm-level components of design capabilities, including patents and industrial design, have not seen significant development and do not play an essential role in accumulating design capabilities in these countries. For V4 countries to advance, firm-level components must complement the development of macrolevel components.

Figure 2

Dynamics of components of design capabilities



The relationship between NTC and GDP per capita in V4 countries is illustrated in Figure 3. The positive trend observed across all countries suggests that economic growth in V4 countries is associated with improved technological capabilities. However, Poland demonstrates a particularly strong accumulation of technological capabilities. This upward trend persists until GDP per capita exceeds 15,000 USD, which begins to level off in Slovakia and the Czech Republic. Despite the overall positive trend, Hungary lags slightly behind the other V4 countries in technological capability accumulation.

The dynamics of implementation and design capabilities concerning national technological capabilities are shown in Figure 4. The trend is positive for both capabilities across all countries. The accumulation of implementation capability is expected to be more intensive at lower levels of national technological capabilities.

As overall technological capabilities develop, the accumulation of implementation capability slows down while design capability takes the lead (Lee et al. 2019). The expected trend for implementation capabilities is generally observable across all countries. On average, implementation capabilities show an increasing trend until national technological capabilities reach a level of 6, after which their accumulation plateaus. However, this trend exhibits significant fluctuations in Slovakia and, to some extent, Hungary. Conversely, the accumulation of design capabilities progresses slowly until national technological capabilities reach a level of 6, accelerating across all countries.

Figure 3

Relationship between national technological capabilities and income level

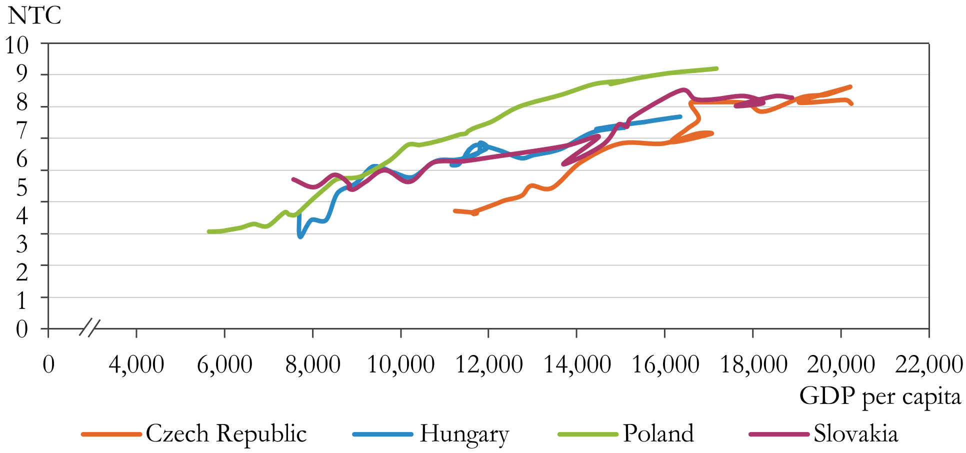


Figure 4

National technological capabilities and

a) implementation capabilities **b) design capabilities**

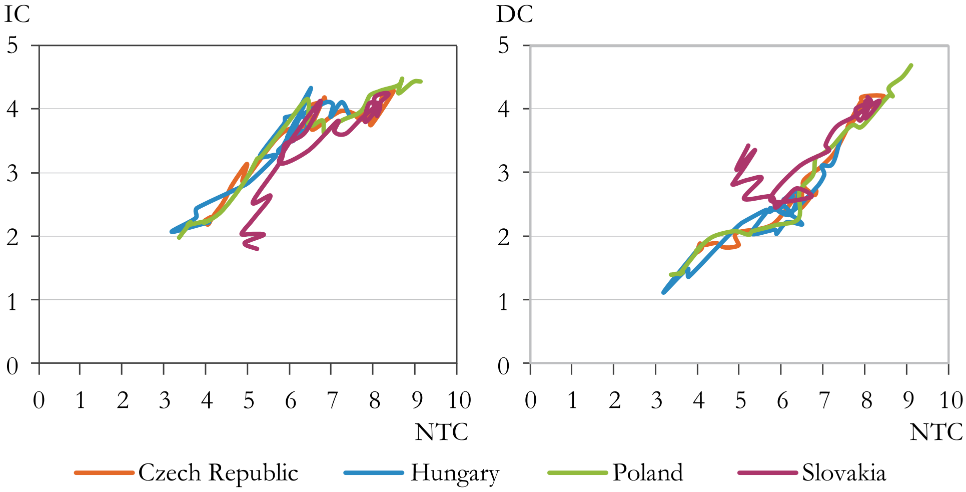


Table 4 shows that the strength of design capabilities within national technological capabilities increased between 1995 and 2022 for V4 countries, except for Slovakia. A closer look at the table reveals that 2010 marks a turning point. Until then, implementation capabilities had remained dominant; however, after 2010, design capabilities increased significantly. V4 countries adopted an FDI-led growth model in the mid-1990s. This model led their economies to specialize in low- and mid-value-added activities that relied heavily on implementation capabilities. However, the 2008–2009 crisis revealed that such specialization could not sustain long-term economic development (Farkas 2020). Therefore, the search for a new growth model that targets higher value-added activities became popular in the public agenda of these countries. This shift may explain the relative development in design capabilities since 2010. Additionally, EU support for R&D may have contributed to progress in design capabilities.

Table 4

The ratio of IC and DC to NTC

Period	Czech Republic		Hungary		Poland		Slovakia	
	IC	DC	IC	DC	IC	DC	IC	DC
1995–1999	0.56	0.44	0.60	0.40	0.60	0.40	0.39	0.61
2000–2004	0.60	0.40	0.60	0.40	0.56	0.44	0.51	0.49
2005–2009	0.60	0.40	0.63	0.37	0.62	0.38	0.57	0.43
2010–2014	0.51	0.49	0.59	0.41	0.54	0.46	0.51	0.49
2015–2022	0.50	0.50	0.58	0.42	0.50	0.50	0.50	0.50

Methodology

Toda–Yamamoto Granger causality test

The Granger causality test was conducted to examine the role of implementation capabilities in accumulating design capabilities. Prior to performing the causality test, the stationarity of the series was tested, revealing that the series was I (1) and I (0) (Table A5). The Toda–Yamamoto Granger causality test was applied (Toda–Yamamoto 1995). The following formula characterizes the test:

$$IC_{i,t} = \alpha_i + \sum_{i=1}^{k+d_{max}} \beta_i DC_{i,t-k} + \sum_{i=1}^{k+d_{max}} \lambda_i IC_{i,t-k} + \varepsilon_{i,t} \quad (2)$$

$$DC_{i,t} = \alpha_i + \sum_{i=1}^{k+d_{max}} c_i IC_{i,t-k} + \sum_{i=1}^{k+d_{max}} d_i DC_{i,t-k} + e_{i,t} \quad (3)$$

where K is the lag order, which was determined to be 3 based on the Akaike information criteria (AIC) in this model. d_{max} represents the highest degree of integration order and is set to 1. The AIC's independence from sample size and error distribution makes it a robust selection criterion. Additionally, the AIC minimizes information loss between the true and estimated models (Cavanaugh–Neath 2019).

Quantile panel regression

It is theoretically expected that implementation capabilities are essential for economic growth at lower stages of economic development. However, their importance diminishes as an economy advances, with design capabilities leading to growth. To capture the impact of these two technological capabilities at different levels of economic development, the panel quantile regression model (PQR) is employed. This model evaluates the varying effects of the two technological capabilities on economic growth at different stages of economic development in V4 countries. The two-step estimator method was applied (Kim–Muller 2004, Canay 2011). The following equations specify the model:

First step

$$LogGDP\_Pc_{i,t} = \beta_0 + \beta_1 IC_{i,t} + \beta_2 DC_{i,t} + \varepsilon_{i,t} + \nu_i \quad (4)$$

Second step

$$LogGDP\_PC_{i,t} = \beta_{\theta 0} + \beta_{\theta 1} IC_{i,t} + \beta_{\theta 2} DC_{i,t} + \varepsilon_{\theta i,t} \quad (5)$$

with $Q_\theta = (\log\_GDP\_PC_{i,t}/IC_{it}, DC_{it} = \beta_{\theta 0} + \beta_{\theta 1} IC_{i,t} + \beta_{\theta 2} DC_{it}$ (6)

where $LogGDP\_PC_{i,t}$ is the natural logarithmic transformation of GDP per capita. The Q_θ $(log\_GDP\_PC_{i,t}/IC_{i,t}, DC_{i,t})$ denotes the *θth* quantile of $LogGDP\_PC_{i,t}$ conditional on the given $IC_{i,t}$, $DC_{i,t}$. The second step of quantile regression is performed in the 0.2 > θ > 0.8 range.

Results and discussion

The Toda–Yamamoto Granger causality test assesses the sequential relationship between capability and design capability. The test results indicate that the past implementation capability predicts the current level of design capability (Table 5). However, the results do not support the reverse relationship. These findings suggest that the development of technological capability follows a sequence from implementation to design capability.

Table 5

Toda–Yamamoto Granger causality test

Dependent variable: IC null hypothesis: DC does not cause IC				Dependent variable: DC null hypothesis: IC does not cause DC			
excluded	chi-sq	df	probability	excluded	chi-sq	df	probability
DC	2.20	2	0.53	IC	9.3465	2	0.025
all	2.20	2	0.53	all	9.3465	2	0.025

The quantile regression results indicate that both IC and DC positively affect economic growth across all income levels (Table 6). As expected, the positive effect of IC on GDP per capita diminishes as income level increases, while the positive impact of DC strengthens. At lower levels of economic development, the ability to produce efficiently at lower costs within existing technologies substantially influences economic growth. Initially, low-income countries benefit from cost competitiveness, allowing them to leverage labour resources effectively in labour-intensive sectors using existing technologies. However, as seen in V4 countries, this advantage may be exhausted as labour resources dedicated to these activities become depleted (Schwabe 2021). As income levels rise and the labour force diminishes, these countries may lose their labour cost competitiveness, slowing the expansion of IC-intensive activities (Keese 2020). Additionally, the profit margins in IC-intensive production are relatively low. Consequently, these low-profit margins may not sustain economic growth at higher income levels as effectively as at lower levels. In contrast, DC-intensive production offers higher profit margins, which can contribute more significantly to economic development, particularly as countries accumulate design capabilities.

Table 6

Panel quantile regression estimates

Percentile	20%	40%	60%	80%
GDP per capita (USD)	8,549	11,470	14,391	17,312
IC	0.33***	0.33***	0.32***	0.28***
	(10.76)	(9.31)	(11.83)	(4.99)
DC	3.16***	4.02***	5.02***	5.78***
	(21.93)	(18.35)	(9.88)	(21.15)
constant	8.54***	8.64***	8.77***	9.10***
	(31.36)	(7.58)	(53.38)	(30.39)
adjusted R-squared	0.54			

Note: ***, **, and * indicate the statistically significant at 1%, 5%, and 10%, respectively.

Conclusion and policy recommendations

This study evaluated the evolutionary changes in technological capabilities in V4 countries and the role of different technological capabilities on economic growth. All countries improved their national technological capabilities, though Hungary slightly lagged. However, the accumulation of technological capabilities begins to plateau as GDP per capita reaches 15,000 USD. As a driver of productivity growth, technological capabilities are necessary for long-run economic development. Therefore, this lack of dynamism could pose a risk to the continued economic development of V4 countries. As theoretically expected, implementation capabilities play a more critical role in the initial stages of technological capability accumulation. Once national technological capabilities reach level 6, implementation capabilities slow down, and design capabilities take the lead. Causality tests also indicate the presence of a sequential pattern, transitioning from implementation to design capabilities. The analysis of the sub-indicators of implementation capabilities presents that manufacturing-related sub-indicators are the main drivers of the positive trends in implementation capabilities. This finding supports the idea that the manufacturing sector is essential for accumulating technological capabilities, enabling efficient production of goods using existing technologies. At the macrolevel, sub-indicators such as R&D and high-tech exports drive the positive trend of design capabilities. In contrast, at the micro level, sub-indicators such as patents and industrial designs exhibit a positive trend only in Poland, a negative trend in Hungary, and remain stable in the Czech Republic. This suggests that firm-level environments do not always complement macrolevel progress in design capabilities. The results of the PQR analysis indicate that implementation and design capabilities positively affect economic growth. While the strength of the effect of implementation capabilities slightly diminishes over time, the impact of design capabilities becomes more pronounced.

V4 countries have been integrated into the European production system through multinational companies (MNCs), which have played a crucial role in modernizing inefficient industries. This modernization has been driven primarily by the accumulation of implementation capability. However, the current specialization in implementation capability risks trapping these economies in low- and middle-value production segments, limiting their ability to catch up with advanced economies. These countries must focus on accumulating design capabilities to move into higher value-added production segments. While macrolevel indicators, such as R&D spending, personnel, and high-tech exports, suggest a positive trend in design capability accumulation, firm-level design capabilities remain underdeveloped. Since innovation and the creation of new products and processes depend on firm-level technological capabilities, regional governments should prioritize their development. Policymakers can support this by subsidizing international patent and design registration costs and providing advisory services to motivate firms to invest in innovation. However, introducing innovative products and processes often requires collaboration beyond individual firms. Therefore, governments should facilitate joint projects between universities, research institutions, and industry. Additionally, start-ups and incubators engaged in commercially promising innovative activities should receive support through various incentive schemes, such as improved access to finance, tax incentives, networking opportunities, public procurements, and export promotions.

The data for the 1990s may not fully reflect reality. During this period, V4 countries had only recently transitioned from the socialist system, and the institutional mechanisms for obtaining certificates, such as ISO certificate and trademark applications, were still underdeveloped. As a result, many firms that qualify for ISO 9001 certification and trademarks may not have applied for them. Therefore, the statistics for these sub-indicators could undermine implementation capabilities in the early years of this study. Further research should analyse the development of firm-level design capabilities and the obstacles they face.

Appendix

Table A1

Description of variables

Indicators	Data source
ISO 9001 certificates	International Standardization Organization
Trademark applications	World Intellectual Property Organization (WIPO)
Manufacturing value added per capita (constant USD 2015)	European Union statistics
Employment in manufacturing sector (thousand)	European Union statistics
GFCF in manufacturing sector (constant USD 2015)	OECD statistics
Patent applications	World Intellectual Property Organization (WIPO)
Industrial design applications	World Intellectual Property Organization (WIPO)
High-tech exports per capita (constant USD 2015)	World Bank development indicators
Researchers in R&D sector	World Bank development indicators
R&D spending (% of GDP)	World Bank development indicators
GDP per capita (constant USD 2015)	World Bank development indicators

Table A2

Descriptive statistics of original data

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
ISO 9001	112	563	411.29	3	1,550
TRADEMARK	112	794	333.46	281	1,773
MANF_VALUE	112	2,302	1,116.64	601.62	5,113.35
MANF_EMPL	112	1,015	197.53	677	1,376
GFCF_MANF	112	9,548.25	5,882.22	1,312	27,670
PATENT	112	1,176	1,229	146	4,676
INDSTR_DESIGN	112	46.31	16.75	9	105
R&D_SPENDING	112	1.02	0.41	0.45	1.99
R&D_PERSONNEL	112	5,588	2,110	3,109	11,578
HIGH-TECH_EXPRT	112	954.7	5,882	1,332.16	27,670

Table A3

Descriptive statistics of sub-indicators

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
ISO 9001	112	0.36	0.26	0.0008	1.00
TRADEMARK	112	0.45	0.19	0.0003	0.99
MANF_VALUE	112	0.45	0.21	0.0002	1.00
MANF_EMPL	112	0.73	0.14	0.0020	1.00
GFCF_MANF	112	0.36	0.21	0.0014	1.00
PATENT	112	0.26	0.27	0.0321	1.00
INDSTR_DESIGN	112	0.44	0.19	0.0031	1.00
R&D_SPENDING	112	0.51	0.20	0.0043	1.00
R&D_PERSONNEL	112	0.48	0.18	0.0007	1.00
HIGH-TECH_EXPRT	112	0.30	0.26	0.0093	1.00

Table A4

Cronbach's alpha and reliability test

Index	Cronbach's alpha	Composite reliability
IC	0.681	0.672
DC	0.782	0.788

Table A5

Levin–Lin–Chu unit root tests

Variable	Level	Difference
IC	–2.01**	–
DC	1.31	–6.23***

Note: ***, **, and * indicate the statistically significant at 1%, 5%, and 10%, respectively.

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