ORIGINAL ARTICLE

Elżbieta Roszko-Wójtowicz
University of Lodz, Poland
 orcid.org/0000-0001-9337-7218

Barbara Dańska-Borsiak
University of Lodz, Poland
 orcid.org/0000-0002-3264-3954

Maria M. Grzelak
University of Lodz, Poland
 orcid.org/0000-0003-4353-9893

Aleksandra Pleśniarska
Cracow University of Economics, Poland
 orcid.org/0000-0003-3257-8416

In search of key determinants of innovativeness in the regions of the Visegrad group countries

Abstract

Research background: Discussions on the state of the economy in times of crisis focus not only on maintaining or improving innovativeness, but also on the emergence of new dimensions of this phenomenon and changing the significance of individual determinants of innovativeness. Innovativeness is a complex, multidimensional and difficult to measure phenomenon, which implies the need to select various indicators and methods for its assessment. Synthetic measures of innova-

tiveness are widely used in comparative analyses, in particular presenting results in international or interregional cross-sections. The degree of innovativeness should also be assessed at different levels of economic aggregation. The lower the level of aggregation, the easier it becomes to capture the specific determinants of the increase in innovativeness of a given area.

Purpose of the article: The main aim of the paper is to attempt to measure the relationship between expenditures and results of innovative activities for NUTS-2 regions of the Visegrad Group countries. Three variables were adopted to describe the effects of innovative activity: PCT patent applications per billion GDP (in PPS), trademark applications per billion GDP (in PPS) and public-private co-publications per million of population.

Methods: The study covered 37 NUTS-2 regions of the Visegrad Group countries in the years 2014–2021. From the point of view of the purpose of the paper and the need to search for the relationship between expenditures on innovative activity and the results of this activity, it is worth emphasizing that the use of static and dynamic econometric models proved to be a substantively correct solution leading to the formulation of clear conclusions.

Findings & value added: The conducted research confirmed that business R&D expenditure on GDP has a positive effect on inventions expressed by patents and trademarks, especially in the long run. In addition, the literature review and empirical analyses indicate that the main determinants of innovativeness (both before and during the pandemic) are the expenditures of economic entities on R&D, competences expressed by the level of education or participation in tertiary education, as well as the number of ICT specialists and the percentage of people employed in science and technology. Despite the deterioration of many macroeconomic indicators in the countries of the Visegrad Group, the expenditures of the business sector on R&D in most regions did not decrease between 2019 and 2021. The added value of the paper is the presented research procedure, which can be used in analyses of innovativeness also for other groups of regions.

Introduction

Innovativeness of economies is an issue that is of particular importance in times of crisis. The economic downturn related to the COVID-19 pandemic, which has been spreading practically around the world since 2020, the outbreak of war in Ukraine, and the social and economic crisis in Europe have a different impact in different countries. Discussions on the state of the economy in times of crisis focus not only on maintaining or improving innovativeness, but also on the emergence of new dimensions of this phenomenon and changing the significance of individual determinants of innovation (Banaszyk *et al*., 2021).

Under conditions of progressing globalisation, only those countries and regions that are competitive can achieve success. An important factor determining the improvement of competitiveness is the development of science along with technical and technological progress, including progress in the digitisation of the economy. Progress results in the emergence of new methods of production, as well as innovative forms of organising the production process and ways of managing human capital. Thus, innovation is the main stimulus for the development of modern economies of the world (see e.g.: Roszko-Wójtowicz & Białek, 2016; Stasiulis, 2017; Doyle & Perez-Alanis, 2017; Roszko-Wójtowicz & Grzelak, 2020; Skalický *et al*.,

2022). Theoretical concepts (see e.g.: Porter, 2008; Castellacci, 2008; Misala, 2014) and the results of many empirical studies (e.g.: Weresa, 2015; Roszko-Wójtowicz & Białek, 2016; Terzic, 2017; Schwab, 2019; IMD, 2020; Akça & Afşar, 2020; Hameed *et al.*, 2021) confirm that the innovativeness of the economy is closely linked to its competitiveness.

Innovativeness is a complex, multidimensional and difficult to measure phenomenon, which implies the need to select various indicators and methods for its assessment (Zygmunt, 2022). The degree of innovativeness should also be assessed at different levels of economic aggregation (see De Carvalho *et al.*, 2017; Roszko-Wójtowicz & Grzelak, 2020; Sinclair-Desgagné, 2022). The macroeconomic comparative perspective ought to be complemented by analyses at the mesoeconomic level presenting the level of innovativeness of regions, as geographical proximity and other related dimensions of this phenomenon, such as cognitive, organisational, social and institutional proximity, play a significant role in the development of innovativeness (Ciołek & Golejewska, 2022; Parrilli *et al.*, 2020; Boschma, 2005). It is in the regions that interaction and cooperation between the actors of innovation systems occur most often.

The subject matter of the research presented in the paper is part of the trend of analysing innovation efficiency. This efficiency is perceived as one of the basic factors of competitiveness of economies, as it allows them to keep up with the developing and changing technology. The relationships between expenditures on innovation and innovativeness, their effects and economic development have been examined in numerous works (see e.g.: Khedhaouria & Thurik, 2017; Lei *et al.*, 2020; Akça & Afşar, 2020; Ivus *et al.*, 2021; Hameed *et al.*, 2021; Lopez-Cabarcos, 2021; Song *et al.*, 2022, Aytekin *et al.*, 2022). Most of these studies were conducted at the national level, only Song, Zhao and Varma (2022) modelled the innovation performance index for 31 provinces in China.

A relatively small number of studies devoted to the analysis of the relationship between expenditures on innovation and innovativeness and their effects in regions, i.e. the levels lower than the national level, results in a certain research gap which the presented paper contributes to filling. Thanks to the use of panel data models, it is possible to estimate the average impact of individual innovation expenditures (PCT patent applications per billion GDP, trademark applications per billion GDP or public-private co-publications per million population) on their effects and to take into account the influence of constant-over-time and unobservable factors specific to particular regions. The use of panel data models in research on regional innovativeness is relatively rare. Such models were used by Hunady *et al.* (2017) to conduct research on the potential relationship between gross

domestic expenditure on R&D and economic development of the V4 regions, by Ciołek and Golejewska (2022) in their research on the effectiveness of regional innovation systems in sub-regions of Poland, as well as by Zhengwen *et al.* (2022) to examine the relationship between science and technology insurance and regional innovation. The added value of this work, in addition to determining the relationship between expenditures on innovation and their effects, is also conducting these analyses on the basis of panel data models.

The main aim of the paper is to attempt to measure the relationship between expenditures and results of innovative activities for NUTS-2 regions of the Visegrad Group countries. It is particularly interesting for research to assess the level of innovativeness in the regional dimension, referring to regions with both a similar past related to economic transformation and the process of European economic integration, as well as those remaining in geographical proximity. In view of the above, the study covered 37 NUTS-2 regions of the Visegrad Group countries in the years 2014–2021. Three variables were adopted to describe the effects of innovative activity: PCT patent applications per billion GDP (in PPS), trademark applications per billion GDP (in PPS) and public-private co-publications per million of population.

In the theoretical section of the paper, selected aspects of innovativeness along with its indicators and determinants are presented. The research method adopted here involves a literature revision. Subsequently, in the empirical section, the results of panel models for NUTS-2 of Visegrad Group are presented. This part of the paper indicates that the activity of enterprises in the R&D sphere, both in the current and preceding period of the study, is one of the key determinants of the level of innovativeness of regions in the Visegrad Group countries. When formulating conclusions from the study, the authors focused on describing the cause-effect relationships between the outcomes and expenditures in the area of innovation. The selected econometric methods proved to be an effective tool in achieving the set goal of the paper, and the obtained results allowed for the formulation of unambiguous conclusions from the study. The conducted research, as well as extensive literature studies, have confirmed that business R&D expenditure on GDP has a positive effect on inventions expressed by patents and trademarks, especially in the long run.

Literature review

The innovativeness of the economy defines the ability and willingness of economic entities to apply research results and R&D work in their business practice (Strahl & Sobczak, 2017). The level of innovativeness of an economy is therefore related to socio-economic development and, consequently, also to international competitiveness. Innovativeness can be analyzed in both the micro- and macroeconomic approaches (Cichy & Gradoń, 2016; Bigos & Michalik, 2020). Žítek *et al.* (2016) emphasize that initially the concept of innovation systems only focused on the national level, and over time it was also applied to the multinational level and regional level. It has been observed that industries concentrate in certain areas and the existing decentralized policy can be applied to the regional level. Szopik-Depczyńska *et al.* (2020) note that 'innovativeness is now recognized as one of the most important factors determining the competitiveness of regions.' Not only the existence of research infrastructure, skilled employees and expenditure on R&D or a high level of GDP are important for the development of innovation in the region (especially regional innovation systems), but also the presence of knowledge-intensive industries, emergence of new technologies in the region, and the creation of relations between businesses and research (Žítek *et al.*, 2016).

Due to the complexity and capacity of the concept of innovation (understood mainly in the context of the implementation of new ideas and inventions), it is extremely difficult to measure development in this multidimensional scope, especially in relation to changes taking place in national economies. It should be noted that subsequent editions of the Oslo Manual mainly refer to statistics measuring innovation in enterprises, while innovations also occur in the public sector or households. As Gault (2018) notes, in order to understand innovativeness in the whole economy, it is important to carry out a broader analysis that takes into account all sectors of the economy. Over the years, as the approach to the very understanding of innovation has evolved, new concepts have emerged in the selection of indicators. In the 1950s, when innovations were associated mainly with technological changes, indicators focused on the so-called input factors, such as R&D expenditure or Science and Technology personnel, dominated. Subsequently, the indicators of the so-called second generation (1970–1980) referred mainly to data on patents or publications. In the 1990s, there were attempts to assess the effectiveness of innovation. Nowadays, innovations (especially in relation to the business sector) are understood not only as technological changes but also changes in processes or services, hence the set of indicators is expanding. Therefore, attention is also paid to the

results of innovations, the process of knowledge creation or the establishment of partnerships and cooperation networks (Chen *et al.*, 2020; Bhattacharya, 2016).

It seems that it is difficult to point at a universal indicator used to measure innovation and innovativeness on a macroeconomic scale. This is due to the fact that only some of the factors determining the ability of enterprises or countries to innovate can be described quantitatively. Usually, the indicators pointed out are: 1) expenditure/input, 2) effect. The basic indicator within the first group is the level of R&D expenditure. Furthermore, Węglarz (2018) notes that the amount of expenditure on R&D (usually in relation to GDP) is one of the most common and basic indicators used to measure the level of innovativeness in the economy. Within the second group, indicators showing the effects of expenditures incurred on R&D (e.g.: the number of scientific publications or patent applications) are usually analysed. It is worth mentioning that innovation indices, which have a synthetic character and are aimed at making international comparisons, apart from the above-mentioned groups of indicators, also take into account the climate for innovation and the business environment (Roszko-Wójtowicz & Białek, 2019; Mikhaylova *et al.*, 2019). Regarding the above-presented theoretical considerations, it is worth emphasizing that innovativeness cannot be equated with and perceived only in the context of R&D. However, it seems that this sector is one of the most important determinants of the innovativeness of an economy. Research shows (Huňady & Pisár, 2021) that business R&D expenditure on GDP has a positive effect on the invention expressed by patents, especially in the long run.

When making a comprehensive assessment of innovativeness in the regional dimension, it is worth paying attention to the role of such factors as R&D expenditure, human resources, technological knowledge diffusion or the impact of patents generation, the development and employment level, and the level of technological diversity on innovation efficiency (Kalapouti *et al.* (2020). Similar conclusions can be drawn from the research on European regions conducted by Szopik-Depczyńska *et al.* (2020). In the cited work, among the analyzed indicators, the authors list the following: R&D expenditure, EPO patent applications, European trademark applications, life-long learning, the percentage of population aged 30–34 having completed tertiary education, and international scientific co-publications per million of population. This confirms the need for research on innovativeness at the regional level aimed at assessing the cause-and-effect relationships between the effects of innovative activity and its potential determinants.

The range of indicators used in the measurement of innovativeness is constantly changing — usually new indicators are constructed, providing the possibility of aggregating quantitative data which are to enable an even more complete assessment. Increasingly, indicators referring to broadly understood digitization are also used in the assessment of the level of innovativeness, which is undoubtedly a consequence of socio-economic changes caused by digital transformation. For example, it is worth pointing to the RIS, which takes into account the level of development of digital skills — this is an indicator that was first used in the analysis in 2021. The greatest number of indicators referring to many dimensions of Information and Communication Technologies (ICT) were included in the GII (e.g.: ICT access, ICT use, government's online services, imports of ICT services and exports of ICT services). Moreover, the study of the relationship between ICT and innovation is also reflected in the literature (e.g.: the relationship between information technology (IT) investments and innovation outcomes (Orozco *et al*., 2022), the relationship between innovation and ICT development for the EU–28 Member States (Preda *et al*., 2019), or the influence of ICTs on enterprise innovation performance (Wang & Qi, 2021).

After conducting an in-depth analysis of selected summary indicators of innovativeness and competitiveness (e.g.: Bello *et al*., 2022; Dutta *et al.* (eds.), 2021; Dutta *et al.* (Eds.), 2014; European Commission, 2014; European Commission, 2019; European Commission, 2021; Hollanders & Es-Sadki, 2021; Jewell, 2021; Roukanas, 2021; Schwab, 2019; UNDP, 2021), those with a European as well as global dimension, several important observations come to mind. It should be noted that the R&D expenditure indicator is included in calculating the summary value of most international indices such as the Global Innovation Index, the European Innovation Scoreboard, the Bloomberg Innovation Index, and the Global Competitiveness Index. Such indicators as patent applications (e.g.: PCT patent applications) and population with tertiary education are indicators quite often used in the aforementioned summary indices (Ervits, 2020). Some indices also include indicators presenting the level of cooperation established between entities, i.e. university-industry R&D collaboration (e.g.: the Global Innovation Index) or international scientific co-publications (e.g.: the European Innovation Scoreboard (EIS) and the Regional Innovation Scoreboard (RIS).

It is worth mentioning that innovation indices, which have a synthetic character and are aimed at making international comparisons, apart from the above-mentioned groups of indicators, also take into account various indicators referring to prerequisites for doing business (Roszko-Wójtowicz & Białek, 2019; Mikhaylova *et al.*, 2019). Research shows that most inno-

vation-related indicators are strongly correlated with the productive struc-
ture of each economy (compare Mamede, 2017; Sharma *et al.* 2022; Kiril-
lova & Uvarova, 2021). Pearson correlation coefficients between most IUS
indicators and the weight of knowledge/technology-intensive manufactur-
ing and services activities in total business employment for the European
countries are statistically significant, e.g.: business R&D expenditure or
PCT patent applications.

The importance of synthetic measures of innovation within comparative
analyses, especially in international cross-sections, has been repeatedly
confirmed in the literature (Roszko-Wójtowicz & Białek, 2019; Mamede,
2017; Roszko-Wójtowicz & Białek, 2016; Roukanas, 2021). However, not
only the methods of multivariate statistical analysis are important in meas-
uring innovativeness. From the point of view of the aim of the paper and
the need to search for a relationship between expenditure on innovative
activities and the results of this activity, it is worth emphasizing that the use
of econometric models is definitely more reasonable and is part of the re-
search on the determinants of innovativeness at the regional level.

Research materials and methods

Research materials

The statistics used in the study are derived from the European Innovation
Scoreboard (European Commission, 2014; Hollanders & Es-Sadki, 2021)
and the Regional Innovation Scoreboard (European Commission, 2021).
Data from 2014 to 2021 for 37 NUTS-2 regions of the Visegrad Group
(V4) countries were used. This group consists of Czechia (or the Czech
Republic), Hungary, Poland, and Slovakia. The classification of territorial
units for statistics (NUTS) was introduced in 2003 by Regulation (EC) No
1059/2003 of the European Parliament. The regulation has been amended
several times with the last amendment introduced in 2017. The NUTS clas-
sification has a hierarchical structure, and each country is assigned three
levels: NUTS-1, NUTS-2 and NUTS-3. Regions at each level are compara-
ble in terms of population. The NUTS-2 level consists of units with a popu-
lation of between 800,000 and 3 million, overlapping as far as possible with
existing administrative units. The current classification distinguishes 8
NUTS-2 regions each in Czechia (or the Czech Republic) and Hungary, 17
regions in Poland, and 4 in Slovakia.

Three variables were adopted in this paper as indicators of regional innovativeness: PCT patent applications per billion GDP (in PPS), trademark applications per billion GDP (in PPS) and public-private co-publications per million of population. Panel data models were used for modelling each of these variables.

Three variables were adopted in this paper to describe the effects of innovative activity:

PCT_appl	PCT patent applications per billion GDP (in PPS)
TM_appl	trademark applications per billion GDP (in PPS)
pp_publ	public-private co-publications per million

The following variables were selected to fulfil the role of potential independent variables in the models measuring the effects of innovative activity:

tert	percentage of population aged 25–34 with tertiary education;
life_lear	the share of population aged 25–64 enrolled in education and training (lifelong learning);
dig_skill	individuals with above basic overall digital skills
RD_publ	R&D expenditure in the public sector as percentage of GDP;
RD_business	R&D expenditure in the business sector as percentage of GDP;
emp_ICT	employed ICT specialists;
emp_know	employment in knowledge-intensive activities
hrst	persons with tertiary education (ISCED) and/or employed in science and technology as percentage of population in the labor force;
intern_publ	international scientific co-publications per million of population.

The selection of variables for modelling was made after the literature review. Trademarks were regarded as an indicator of regional innovativeness in the work of Block *et al.* (2022), while Burhan *et al.* (2017) measured innovation based on the number of patent applications. The set of proposed potential independent variables includes variables representing financial expenditures (*RD_publ* and *RD_bizn*), variables describing the potential of human resources (*tert*, *life_lear*, *dig_skill*, *intern_publ*) and variables showing employment in areas related to science and research as well

as information and communication technologies (*emp_ICT*, *emp_know*, *hrst*). The role of public and private R&D expenditures and employment in the indicated areas as well as human resources in shaping innovativeness is commonly recognized in the literature (see, e.g.: Silaghi *et al*., 2014; Hunady *et al*., 2017; Athreye & Wunsch-Vincent, 2021; Hameed *et al*., 2021; Lopez-Cabarcos, 2021). Basic statistics of variables used in the research for the first and last period of analysis are presented in Table 1.

The indicators included in Table 1 were calculated on the basis of data from 37 NUTS-2 regions of the V4 countries for the indicated years. Between 2014 a 2021, there was a noticeable increase in the average value of all variables describing the effects of innovative activity (*PCT_appl*, *TM_appl*, *pp_publ*). On average, the number of public-private co-publications per million population grew at the fastest rate year by year, and the number of PCT patent applications rose at the slowest rate — only by approx. 0.4% (see the value of T_n in Table1). A significant increase (on average of nearly 8%) was also recorded in the case of R&D expenditure in the business sector. At the same time, public sector expenditure in the years 2014–2021 decreased on average by 0.4% year by year, but this result was influenced by the decrease in the value of the variable in 2019 to 70% of the value from 2018. In other periods, these expenditures increased by 2–8% compared to the previous year. The other variables were characterized by a moderate average annual rate of change, which was negative in the case of lifelong learning. The variation of most variables in 2021 was lower than in 2014 (see the values of V in Table 1), therefore the effects of and expenditure on innovative activity were more and more evenly distributed in the analyzed period.

According to data of the European Commission (2021), the highest values of variables representing effects of innovative activity were recorded in the capital city regions. However, it can be seen that being a leader in one of these areas does not necessarily mean leadership in the other area as well. In terms of the number of patent applications per billion GDP, the Hungarian regions of Budapest and Pest were the leaders (almost every year). A very large number of patent applications was recorded in the Czech region of Severovýchod. At the same time, the largest number of trademark applications per billion GDP was recorded in the capital region of Warsaw as well as in Praha and Bratislavský kraj. The leading regions in terms of the number of public-private co-publications per million of population were Praha and Budapest.

Based on the collected data, it can be said that the capital regions of the Visegrad countries are characterized by a relatively the highest level of innovation. In Hungary, high business R&D expenditures are characteristic of the region of Budapest (2.010 in 2021 and 1.740 in 2020). The leading regions in terms of R&D activity of enterprises in Poland are the Warsaw Capital region (1.740 in 2021 and 1.550 in 2020) and the Małopolski region (1.410 in 2021 and 1.170 in 2020). In the case of the above-mentioned regions, an upward trend is also observed for the indicator in question. In the case of Slovakia, the highest values of business R&D expenditures were recorded for Bratislavský kraj (0.770 in 2020 and 0.630 in 2021). Nevertheless, the Slovak regions perform the worst among the entire Visegrad group in terms of business R&D expenditure. In the case of variables used in the panel data models presented in this paper, the region of Strední Cechy (Czechia) is a definite leader in terms of R&D expenditures in the business sector, with the value of the indicator of 2.090 in 2021 and 1.870 in 2020. It is an exception here, as it is not a capital region. Nevertheless, its location in the center of the country and close links to Prague create good opportunities and conditions for employment and the development of business activities. A large share of Stredni Cechy in the total Czech industrial output is the real strength of this region.

In most regions (32 out of 37) of the Visegrad Group countries, no decrease in R&D expenditures in the business sector was observed in the years 2019–2021 (European Commission, 2021). Moreover, in some of the regions, there was at least a doubling of the value of the indicator, e.g. in the Świętokrzyskie, Podlaskie, Opolskie and Lubuskie Voivodships in Poland and in the Dél-Dunántúl and Pest regions in Hungary. No region in Czechia (or the Czech Republic) or Slovakia recorded such spectacular increases. In general, the Slovak regions recorded the lowest values of business expenditures on R&D in the pandemic period. With regard to patent applications or trademark applications, it can be seen that being a leader in one of these areas does not necessarily mean leadership in the other area as well. For instance, in Czechia (or the Czech Republic), the highest values for trademark applications are recorded in the Praha (Prague) region (6.977 in 2021), whereas the largest number of PCT applications was recorded in Severovýchod — 1.134 in 2021 and 1.023 in 2020, and in Strední Cechy in 2019 — 1.398 (European Commission, 2021). Generally, in the entire V4 group, the highest values of trademark applications are registered in the capital regions.

Methods

Panel data models are used for modelling each of the three variables describing effects of innovative activity (*PCT_appl*, *TM_appl*, *pp_publ*). The results of the estimation of these models will be the basis of the verification of the main hypothesis:

R&D expenditure is one of the basic determinants of effects of innovative activity in the regions of the Visegrad Group countries.

Additionally, the following specific hypotheses will be verified:

H1: *The effects of innovative activity in the regions of the Visegrad Group countries appear in the economy with a certain lag in relation to the expenditure incurred.*

H2: *The effects of cooperation between enterprises and the scientific community expressed in the number of public-private co-publications depend on business R&D expenditure.*

H3: *The potential of human resources and the size of employment in areas of science and research as well as information and communication technologies have a positive effect on innovative activity in the regions of the Visegrad Group.*

The models were estimated on the basis of time-series cross-sectional data for 37 regions and 8 years, obtaining identical estimates of structural parameters for all regions and periods. Panel data models are estimated on the basis of panel data for all regions and periods, which allows us to determine identical estimations of structural parameters for all regions. At the same time, region-specific group effects are distinguished, reflecting the cumulative effect that constant over time, unobservable factors which cannot be included *explicite* as independent variables have on the dependent variable. If such non-identifiable impulses actually occur, failure to include them in the model causes the omitted variable problem, which in turn translates into biased estimators, i.e. omitted variable bias. Estimating the model on the basis of panel data taking into account group effects makes it possible to solve this problem which is well-described in the econometric literature (e.g. Chamberlain, 1978). If the right procedure is not applied to solve this problem, this may lead to spurious correlations. The most general specification of a static panel data model is:

$$y_{it} = x_{it}^T\beta + u_{it} = x_{it}^T\beta + (\alpha_i + \varepsilon_{it}) \qquad (1)$$

where:

x_{it} vector of independent variables,

β vector of structural parameters,

$i = 1, ..., N$ object number,

$t = 1, ...,$

T period number,

$\varepsilon = [\varepsilon_{it}]$ 'classical' random component: $\varepsilon \sim N(0, \sigma_\varepsilon^2 I)$,

α_i group effect, constant over time.

Group effects can be treated as fixed effects (FE) or random effects (RE). In the former case, in the estimation and inference process, they are treated as fixed parameters to be estimated (group — specific constant), while in the latter case as components of an error term. The FE model requires only the assumption that the elements of vector x_{it} are independent of ε_{it} for all i, t, and α_i are treated as N of unknown parameters subject to estimation. Whereas, in the RE model, it must be assumed that the elements of vector x_{it}, α_i and ε_{it} are independent and that $\alpha_i \sim N(0, \sigma_\alpha^2)$. The consequence of adopting the FE or RE specification is the application of an appropriate model estimation method. FE models are estimated using the Within Group estimator, based on the Ordinary Least Squares Method (OLS), while RE models are estimated using the specific type of Generalized Least Squares. The significance of group effects in FE models is tested using the Chow test, and in RE models using the Lagrange multiplier Breusch-Pagan test. The choice between the two types of models can be made on the basis of the Hausman specification test. It allows us to verify whether the key assumption for the correctness of the RE specification, that the elements of vector x_{it}, α_i and ε_{it} are independent, is met. Methods of estimation and testing of panel models are discussed in detail, e.g.: in Baltagi (2021) and Tsionas (ed.) (2019).

The above-presented bibliographic references also include a discussion of the assumptions and methods of estimating and testing dynamic panel data models. Such a model has the following form:

$$y_{it} = \beta_0 y_{i,t-1} + x_{it}^T\beta + u_{it} = \beta_0 y_{i,t-1} + x_{it}^T\beta + (\alpha_i + \varepsilon_{it}) \quad (2)$$

where:

$y_{i,t-1}$ the value of the dependent variable with a lag of one period,

β_0 a parameter, and the other symbols are as in formula (1).

For the estimation of model (2), separate methods are used, different from the ones applied in model (1). Since y_{it} is dependent on α_i, therefore: $y_{i,t-1}$ is also dependent on α_i constant over time. Therefore, $y_{i,t-1}$, a left-hand side regressor in (2), is correlated with the error term $u_{it} = (\alpha_i + \varepsilon_{it})$. For this reason, the OLS estimator would be biased and inconsistent.

The majority of estimation methods of dynamic panel data models are based on the Generalized Method of Moments (GMM). The most often used is the system-GMM estimator developed by Blundell and Bond (1998). Their approach was used in this study. The alternatives would be the first-differenced GMM estimator proposed by Arellano and Bond (1991) or the instrumental variables technique by Anderson and Hsiao (1982). The system-GMM estimator has better properties than the latter in the case of regressor endogeneity and short time dimension of the panel. It is much more effective than the first-differenced GMM, especially if the autoregressive parameter is close to one or the ratio of the group effects variance to the error term variance is growing.

The system-GMM estimator can produce consistent estimates only if the moment conditions used are valid. Two tests can be used: the Arrelano-Bond autocorrelation test and the Sargan test of overidentifying restrictions. The former tests serial autocorrelation in the first-differenced errors. The first order correlation in the differenced equation is acceptable by assumption, but the hypothesis of the second order correlation should be rejected if the moment conditions are valid. The latter tests for the validity of the overidentifying restrictions.

Results

In the course of the research, three econometric models explaining the variables describing the effects of innovative activity in the regions of the Visegrad countries were estimated. These are three variables: PCT patent applications per billion GDP (in PPS), trademark applications per billion GDP (in PPS) and public-private co-publications per million of population. An econometric model describing its creation was estimated for each of these variables. Various forms of panel data models were tested, taking into consideration both the set of independent variables and the functional form. The selection of potential independent variables is justified in the "Research materials and methods" section. The results of estimation of models that were considered the best from the point of view of statistical-econometric properties and substantive interpretation are presented below.

Decisions were made on the basis of the results of the relevant tests indicated below and economic theory.

PCT patent applications

PCT patent applications per billion GDP in Purchasing Power Standards (*PCT_appl*) constituted the dependent variable of the first model. Its creation was described by dynamic model (2), and the independent variables included: employed ICT specialists (*empl_ICT*), lifelong learning — the share of population aged 25–64 enrolled in education and training (*life_learn*), R&D expenditure in the business sector as percentage of GDP (*RD_business*) lagged by one year, and international scientific co-publications per million of population (*intern_publ*). The results are presented in Table 2.

The *emp_ICT* independent variable was treated as endogenous. This means that it can be correlated with the current and lagged values of the error term ε_{it}. Employment in the ICT sector is linked to total employment, which in turn is a derivative of the general economic situation of the region and the country. These factors are not included in the model, so they can be reflected in the random component and cause correlation. The assumption of endogeneity of *emp_ICT* was confirmed by an improvement in model quality — all variables became statistically significant at the level of 0.05. The Arrelano-Bond autocorrelation test and the Sargan test were used to test the quality of the model. Based on the values of the test statistics in Table 2, there is no basis for rejecting the null hypothesis in both cases. This means that the model parameter estimators are consistent and unbiased. An increase in each variable leads to an increase in the number of patent applications. A very strong influence on the number of PCT patent applications is exerted by R&D expenditure in the business sector from the previous year. This reflects the length of the research processes preceding the patent application. The impact of employment in the ICT sector (*empl_ICT*) and lifelong learning (*life_learn*) is similar. The number of PCT patent applications is also strongly determined by the number of such applications in the previous year. Due to the linear form of the model, the numerical values of all parameter estimations are interpreted as marginal values.

Trademark applications

Trademark applications per billion GDP in Purchasing Power Standards (*TM_appl*) constitute another dependent variable. Its creation is described

by static model (1) with fixed group effects (FE). The independent variables included: R&D expenditure in the business sector as percentage of GDP (*RD_business*) current and lagged by one year as well as percentage of population aged 25–34 with tertiary education (*tert*). The results are presented in Table 3.

According to the results of the Hausman test, the null hypothesis about the lack of correlation of group effects with independent variables should be rejected. This means that the estimator of the RE model would be biased. Table 4 therefore contains the results of the FE model estimation. Group effects in this model are statistically significant, as evidenced by the results of the Chow test. This means that the dependent variable, in addition to the variables included in the model, is affected by unobservable factors, constant over time and specific to individual regions.

The trademark applications model, similarly to the PCT-patent applications model, has a linear form, hence the numerical values of parameter estimations are interpreted *ceteris paribus* as marginal values. There is a very strong, positive impact of the increase in R&D expenditure in the business sector on the growth in the number of trademark applications, with the impact of expenditures incurred in the previous year being much stronger than the impact of current expenditures. This reflects the length of the research processes preceding the patent application. The impact of percentage of population with tertiary education is weaker, although also statistically significant and positive.

Public-private co-publications

Public-private co-publications per million of population (*pp_publ*) constitute another dependent variable. Its creation is described by static model (1) with fixed group effects (FE). The independent variables included: persons with tertiary education (ISCED) and/or employed in science and technology as percentage of population in the labour force (*hrst*), R&D expenditure in the business sector as percentage of GDP (*RD_business*) current and lagged by one year, as well as employed ICT specialists (*empl_ICT*). The results are presented in Table 4.

Table 4 presents the results of the FE model estimation, since the parameter estimators are, according to the results of the Hausman test, unbiased. The high value of the test statistic allows for rejecting the null hypothesis about the lack of bias of the RE model estimators. Group effects in the FE model are statistically significant, as evidenced by the result of the Chow test. This means that the number of public-private co-publications

depends not only on the independent variables of the model, but also on unobservable factors, constant over time and specific to individual regions.

The number of public-private co-publications per million of population is most strongly influenced by R&D expenditure in the business sector, both current and lagged by one period. Also in the case of private co-publications, the impact of lagged expenditures is stronger than current ones. This is due to the length of research work required and the waiting time for publication in reputable journals. The impact of the other two variables is also statistically significant and positive, although slightly weaker. The discussed model, similarly to both models presented earlier, has a linear form. Parameter estimations are therefore, *ceteris paribus*, marginal values.

The conducted research provides the basis for the verification of the formulated research hypotheses. The main hypothesis that R&D expenditure is one of the basic determinants of the effects of innovative activity in the regions of the Visegrad countries has been confirmed in terms of the impact of business R&D expenditure. This variable is significant in all the models, but its influence is definitely stronger than that of other independent variables. In addition, the effects of innovative activity are lagged in relation to business R&D expenditure by one year, though the values of trademark applications and public-private co-publications also depend on current expenditure. This means that the specific hypotheses H1 and H2 have been verified positively. Hypothesis H3 on the positive impact of the potential of human resources and employment in areas related to science and research as well as information and communication technologies on the effects of innovative activity in the regions of the Visegrad countries has been also verified. Variables representing this potential are significant in the models for patent applications (*life_lear* and *intern_publ* variables) and in the model for trademark applications (*tert* variable). In the case of public-private co-publications, the impact of *emp_ICT* and *hrst* variables, representing the size of employment in areas related to science and research as well as information and communication technologies, is significant.

Discussion

The literature lacks publications concerning the issues related to the innovativeness of the regions of the Visegrad countries in the context of assessing the relationship between expenditures (inputs) and effects (outputs) of innovative activity. The novelty of the presented research lies therefore in the context of the analysed issue and the level of aggregation — the V4

regions. Thus, the paper contributes novel elements to the development of research concerning the innovativeness of the V4 regions. The literature review, as well as the authors' own empirical analyses, indicate that one of the main determinants of innovativeness (both before and during the pandemic) are expenditures of the business sector on R&D (e.g. Huňady & Pisár, 2021; Firlej, 2019) as well as education expressed through participation in lifelong learning and the percentage of people with tertiary education (e.g. Denkowska *et al.*, 2020). Employed ICT specialists and the percentage of labour force population employed in science and technology (e.g. Pylak & Wojnicka-Sycz, 2017) are also chief determinants of the regions' innovativeness. The latter share is an important determinant in the case of public-private co-publications per million of population.

Research shows that investments in and expenditures on research and development are important for the creation of inventions and innovations (see Huňady & Pisár, 2021) and are statistically significant as far as the economic growth in the EU countries is concerned (see Freimane & Bāliņa, 2016). For many years, investing in R&D has been among the priorities of the European Commission's policy for sustainable socio-economic development in the European Union. Assumptions regarding expenditure incurred both by the private and public sectors were part of Europe 2020 Strategy (pillar — smart growth) (compare Pleśniarska, 2018; Duľová Spišáková *et al.*, 2019; Sochuľáková, 2020). The empirical research presented in this paper indicates that R&D expenditure in the business sector plays a very large role in shaping each of the dependent variables. R&D expenditure in the public sector was insignificant in all the models. A similar regularity in explaining growth of CEE countries was observed by Silaghi *et al.* (2014). In turn, Athreye and Wunsch-Vincent (2021) emphasize that public R&D plays a crucial role in technological advances and development. They also point out that the creation of innovations of commercial significance in business sectors depends on public research. The positive impact of direct government funding of R&D performed by companies on business financed R&D was also indicated by Guellec and van Pottelsberghe de la Potterie (2000).

Panel data models used in the presented empirical research have been utilized in research on innovativeness, among others, by Raymond *et al.* (2015), Akça and Afşar, (2020) or Hameed *et al.* (2021). The research results of Raymond *et al.* (2015) provided evidence of robust unidirectional causality from innovation to productivity in Dutch and French manufacturing companies. According to Akça and Afşar (2020), in 16 OECD countries, the increase in patent applications and R&D investments had a positive effect on economic growth. The study by Hameed *et al.* (2021) sug-

gests that the government can increase innovation by channelizing the economic innovation system indicators through the dynamic capabilities (DC) framework. However, none of these studies have been used to assess the relationship between inputs and outputs of innovative activity at the level of regions of a selected group of countries. In addition, on the basis of fixed effects panel data models for NUTS-2 regions of the V4 countries in the years 2001–2014, Hunady *et al.* (2017) found positive, nonlinear influence of GDP per capita on R&D expenditures. Besides, the authors emphasize lower innovation capacity of less developed regions, which means that they invest in innovation much less than well-developed regions. This is consistent with the conclusions drawn by the authors of this paper. The analysis of individual variables shows that metropolitan regions are characterized by higher innovation capacity.

Ciołek and Golejewska (2022) found the positive effect of regional market size, standard of living and social proximity on the efficiency of innovation processes in Polish subregions. The study was conducted for 72 Polish NUTS-3 subregions in the years 2005–2016. Zhengwen *et al.* (2022) applied a dynamic panel data model to examine the impact of S&T insurance on regional innovation. Their data covered 31 provinces in China in the years 2010–2019. They found a lagged, significant promotion effect of S&T insurance on innovation inputs but a negative effect on innovation outputs. Both studies confirm the legitimacy of conducting analyses in the area of innovativeness at the regional level of NUTS-2 and NUTS-3.

Referring to the subject-related scope of the research (the Visegrad Group) presented in this paper, it is worth mentioning the research conducted by Janoskova and Kral (2019), which focused on identifying the strengths and weaknesses of the national innovation systems of these countries in relation to the indicators used in European Innovation Scoreboards. The authors note that Czechia (or the Czech Republic) occupies the best position among all V4 countries, and Poland the worst. They also emphasize the discrepancies between the countries which can be observed within individual categories. Janoskova and Kral (2019) also note that research on innovativeness is extremely complex, and that making a complete analysis is particularly difficult. Many researchers have also attempted to assess the level of innovativeness and competitiveness of the V4 regions (Ivanová & Masárová, 2018b). For example, it is worth mentioning the research conducted by Golejewska, (2013) which emphasizes the existence of significant differences between these regions in terms of competitiveness and innovativeness. Czupich's research (2018) presents some interesting conclusions: the innovation potential of the regions of the Visegrad Group countries is relatively low compared to the EU average, the highest rates of

innovation potential are achieved by the Czech and Hungarian regions, especially in the field of private R&D expenditure, lifelong learning, employment in the high-tech sector, and patent activity.

A higher level of innovation capacity means that the capital regions are characterized by a relatively high level of innovation, as evidenced by data used to construct the model presented in the paper. This is related to the higher level of entrepreneurship as well as the presence of universities, research institutions and foreign investments in capital regions (Roszko-Wójtowicz *et al*., 2019; Roszko-Wójtowicz & Grzelak, 2021). Ivanová and Masárová (2018a) have also confirmed the relatively best results achieved by the capital regions of the Visegrad Group countries. In addition, they note that the biggest relative differences in innovation performance between the Visegrad Group regions concern the following indicators: public-private co-publications, international scientific co-publications, SMEs with marketing or organizational innovations and innovative SMEs collaborating with others, while the smallest differences occur in: exports of medium high/ high-technology intensive manufacturing, most cited scientific publications, and trademark applications (Ivanová & Masárová, 2019; Alpaslan & Ali, 2017).

Conclusions

The conducted theoretical and empirical considerations confirm that innovativeness is a complex phenomenon which is difficult to unequivocally assess. The authors of the paper have concluded that the multifaceted nature and complexity of the 'innovativeness' phenomenon means that the analysis of one-dimensional dependencies does not provide sufficient grounds for assessing the innovativeness of a country/region and its position in relation to others. Innovations require investments, the basic measure of which is expenditure on R&D. In the regions of the Visegrad countries, business R&D expenditure still does not reach a sufficient level. Nevertheless, a positive trend expressed by the gradually increasing share of business in financing research is being observed. Apart from expenditure on R&D, an insufficient scope of cooperation in its various dimensions (science with business, large enterprises with small ones, domestic scientists with foreign partners, etc.) is also often mentioned among the reasons for the relatively low innovativeness. These problems, especially financial issues and the demand barrier, may become even more troublesome during the COVID-19 pandemic and the war in Ukraine due to the economic slowdown occurring not only in regions of the Visegrad Group countries

but also all over Europe. Increasing cooperation in the field of research and innovation between the V4 regions as well as with other economic partners is undoubtedly one of the conditions for ensuring further development of individual regions of the Visegrad Group and enabling them to eliminate the differences that occur in the level of their innovativeness.

The presented results in the form of panel data models are the product of extensive research work. The paper presents three models for selected output variables in which the obtained values of independent variables proved to be statistically significant. In addition, the direction of the relationship between the independent variables and the dependent variable was substantively justified in the literature. The conducted econometric analysis with the use of static or dynamic panel data models has allowed us to assess the strength and direction of the relationship between expenditures and effects of innovative activities for the NUTS-2 regions of the Visegrad Group countries in the years 2014–2021. Thus, the main aim of the paper has been accomplished. Innovativeness in terms of the results achieved was characterized by three indicators: PCT patent applications per billion GDP (in PPS), trademark applications per billion GDP (in PPS) and public-private co-publications per million of population. The verification of panel data models allows us to conclude that regardless of the variable measuring the innovativeness of regions (the number of patent applications, the number of trademark applications, or the number of public-private co-publications), the most important factor determining its level is R&D expenditure in the business sector, both from the current and preceding period. The effects of enterprises' activity in the R&D sphere are lagged, but may already be visible in the next year after incurring the expenditure. Therefore, supporting the business sector in the area of R&D must be underpinned by a long-term strategy.

This means that the results of empirical work presented in the paper are especially useful for groups of decision-makers in local and central government administration, as well as for business environment institutions and academia. The results of theoretical considerations and the authors' empirical research presented in the paper may help regional authorities to develop better strategies focusing on areas requiring financial support. At the institutional level, they can be a valuable source of information for decision-makers developing future assumptions of the strategic directions of the European Union's development, designing financial support for those areas that actually need it. Drawing attention to the need for changes in the system of official statistics is an important conclusion derived from the conducted research. The difficulty of obtaining data and the incompleteness of data constitute a barrier to undertaking more in-depth research.

Despite our best effort to ensure appropriate data and methodology, there are still some potential limitations. Efforts have been made to take into account the potential endogeneity of the independent variables used in the models. The problem may lie in the omitted-variable bias, as the selection of control variables was limited by the availability of data. Some data in the Regional Innovation Summary are only available as normalized values and could not be used in modelling. These are data on non-R&D innovation expenditures, employment in innovative enterprises, SMEs introducing product or business process innovations or innovative SMEs collaborating with others.

The authors plan to complement the macroeconomic comparative perspective with an in-depth mesoeconomic analysis presenting the list of individual regions of the country in terms of their technological development against the background of the level of innovativeness of the entire economy. The Visegrad Group countries must face the ongoing digitization processes which will allow the level of digitization to be equalized in the Member States of the European Union. It is therefore worth supporting cooperation within the region, which will allow the development of new technologies and increase the competitiveness of economies in comparison with the other countries of the Community. The development of innovativeness in the region is the result of many processes and phenomena of a social, economic or spatial nature, and determining the appropriate level of measurement is a constant challenge for economists. In future research, it is worth focusing on the specificity of regional innovation systems and evaluating, among others, business environment institutions that are responsible for the effectiveness of innovation processes in the region.

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Annex

Table 1. Basic statistics of variables used in the research

Variable	2014		2021		T_n
	Mean	**V**	**Mean**	**V**	
PCT_apl	0.606	71.006	0.625	57.208	0.386
TM_apl	2.154	49.441	3.304	45.037	5.492
pp_publ	79.051	130.164	127.332	110.938	6.140
RD_publ	0.396	73.113	0.382	71.111	-0.439
RD_bizn	0.411	88.080	0.746	66.400	7.746
tert	35.297	29.764	36.784	30.076	0.517
life_lear	6.454	46.991	5.373	43.705	-2.266
dig_skill	19.393	23.664	23.579	10.993	2.473
emp_ICT	2.717	82.436	3.217	80.525	2.137
emp_know	12.114	50.208	15.508	33.829	3.136
hrst	36.222	24.556	41.992	24.088	1.865
intern_publ	468.582	143.682	824.520	121.166	7.319

Table 2. Estimation results for the PCT patent application model

Variable	Coefficient	Std. error	p-value
PCT_appl(-1)	0.301	0.086	0.000
empl_ICT	0.067	0.038	0.074
life_learn	0.059	0.018	0.001
RD_business(-1)	0.152	0.073	0.037
inern_publ	0.0002	0.0001	0.050
Arellano-Bond test	m_1 = -3.818	p-value = 0.000	
	m_2 = -1.564	p-value = 0.118	
Sargan test	chi2(53) = 80.645	p-value = 0.109	

Note: V – means coefficient of variation.

Source: own elaboration based on data from European Commission (2021).

Table 3. Estimation results for the fixed effects model of the trademark applications variable

Variable	Coefficient	Std. error	p-value
RD_business	0.577	0.299	0.054
RD_business(-1)	1.004	0.312	0.001
tert	0.038	0.016	0.021
constant	0.736	0.576	0.202
fraction of variance due to α_i		0.759	
Chow test	$F(36.\ 219) = 14.23$	p-value = 0.000	
Hausman test	8.21	p-value = 0.042	

Note: (-1) next to the name of the variable means a lag of one period.

Source: own elaboration based on data from European Commission (2021).

Table 4. Estimation results for the fixed effects model of the pp_publ variable

Variable	Coefficient	Std. error	p-value
hrst	3.422	0.554	0.000
RD_business	17.812	9.203	0.049
RD_business(-1)	20.694	8.978	0.026
emp_ICT	6.321	2.711	0.021
constant	-64.362	80.838	0.001
fraction of variance due to α_i		0.973	
Chow test	$F(36.\ 218) = 105.89$	p-value = 0.000	
Hausman test	56.39	p-value = 0.000	

Note: (-1) next to the name of the variable means a lag of one period.

Source: own elaboration based on data from European Commission (2021).