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DETERMINANTS OF SPATIAL VARIATIONS IN ECONOMIC GROWTH: A GRAVITY MODEL OF THE EU COUNTRIES IN 2000-2021

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ABSTRACT. This article presents the results of an assessment of the influence of the capital-labour ratio and total gravity effects on labour productivity. The analysis is based on the gravity model of economic growth wherein the distance is measured using the haversine formula, which makes for an innovative approach to the issue. The analysis covers 27 countries of the European Union from the year 2000 to 2021. The availability of data determined this time range, however, it is sufficient for achieving the objective of the article, that is, capturing the relationship between the labour productivity, gravity effects and the capital-labour ratio. Data was retrieved from the database maintained by the United Nations Economic Commission for Europe. This article puts forward two hypotheses. The first hypothesis is that an increase in the capital-labour ratio has a positive effect on the growth in labour productivity. The second hypothesis assumes that a greater geometric mean of the squares of the distances between the capital city of a European Union country and the capital cities of its neighbours has a negative effect on labour productivity. The research findings confirm both hypotheses, highlighting the significance of the capital-labour ratio's effect on labour productivity.

JEL Classification: E27, O11

Keywords: labour productivity, gravity effect, physical capital, capital-labour ratio, linear regression model, classical least squares method.

Introduction

Numerous studies have been conducted on the subject of labour productivity. A substantial number of them aimed to identify the factors that influence labour dynamics (Li & Liu, 2012; Agrawal et al., 2017; Kekezi, 2021). Other researchers adopted a non-standard approach to the topic, focusing on potentially remote and indirect factors, such as the effect of economic crises (Astorquiza Bustos et al., 2022; Auzina-Emsina, 2014; Giannakis and

Mamuneas, 2022), digital infrastructure development (Remeikienė et al., 2022; Staniec et al., 2023) or climate change on labour productivity. The methods used to verify hypotheses about labour productivity are also very diverse. These methods include Data Envelopment Analysis (Li and Liu, 2012), linear regression models (Herman, 2020), the Cobb-Douglas function in its intensive form (Kekezi, 2021), institutional analysis (Jarmołowicz and Kuźmar, 2015; Dinu et al, 2024), General Oligopolistic Equilibrium (Basile and De Benedictis, 2007) or *sigma* and *beta* convergence analysis (Adamowicz and Szepeluk, 2020).

This paper is part of a growing body of research in labour productivity analysis focused on international processes. The study considers spatial interaction in the single European Union (EU) market. The analysis covers the period from 2000 to 2021. The research objective is to assess the properties of the relationship between labour productivity and physical capital, as well as between labour productivity and the geographical distance between the capital cities of the EU countries. Physical capital is considered to be a stimulant of labour productivity. It includes not only the tangible equipment of workstations, but also technical progress embodied in that equipment. In our approach, the geographical distance is viewed as a determinant of the pace at which transactions are concluded in the markets of factors of production and goods. The research assumption is that the greater the technical equipment of workstations (capital-labour ratio in the national economy) and the lesser the distance between countries, the greater the labour productivity. This phenomenon is also known as the gravity effect. Its underlying premise is that the interaction between states or regions is akin to that described by Newton's law of gravitation. The force of such interaction is directly proportional to the product of the objects' sizes and inversely proportional to the square of the distance between them. Gravity models have been widely used to describe trade processes, yet they are infrequently applied in analysis of spatial variations in labour productivity (Mroczek et al., 2014).

To examine the relationship between labour productivity, physical capital and the geographical distance, this study employs the gravity model in the formulation proposed by Filipowicz, Kelebaj and Tokarski (2023). However, the definition of geographical distance used in this analysis differs from that adopted in their study. Specifically, it's calculated using the haversine formula, which determines the distance between two points based on their geographical coordinates while accounting for the Earth's spherical shape. To date, this approach has not been applied in the context of the gravity model, where distances are typically approximated using a straight-line measure derived from Pythagoras' theorem.

This article proposes two hypotheses. The first says that an increase in the capital-labour ratio positively influences labour productivity growth. The second says that a greater geometric mean of the squared distances between the capital city of an EU country and the capitals of its neighbouring countries has a negative effect on labour productivity.

The article is structured as follows: The first section reviews recent studies on labour productivity and its determinants on both regional and national levels. The discussion then turns to the gravity model, the role of distance in this model and the data used to verify the hypotheses. Another section presents the linear regression model, its results and their interpretation. The final section outlines the conclusions drawn from the analysis and discusses the limitations of the adopted approach.

1. Literature review

Giannakis and Mamuneas (2022) examined the sensitivity of changes in labour productivity to economic crisis. Using the Spatial Durbin Error Model, they demonstrated that regions characterized by greater economic pull capacity in the construction sector and higher levels of industrial concentration are better equipped to withstand the negative effects of economic shock and recover more rapidly. They concluded that implementing a territory-oriented policy, based on building regions' competitive strengths, reduces the negative effects of economic shocks and accelerates post-crisis recovery of regional labour markets. Auzina-Emsina (2014) investigated changes in labour productivity and economic growth during the post-crisis period, comparing them with trends observed before and during the 2008+. Her analysis indicated that sustaining or increasing labour productivity during a crisis is the most important factor that stabilizes an economy. In turn, Szewczyk, Mongelli and Ciscar (2011) analyzed a potential fall in labour productivity due to heat stress caused by climate change, i.e. an increase in global temperatures. The study covered 269 European regions and used various sets of climate scenarios distinguished by heat stress indicator values. Their findings revealed a negative effect of heat stress on labour productivity. Scenario analyses further suggested that southern and eastern European regions are most exposed to heat stress which will affect the future dynamics of their labour productivity.

An interesting methodological idea is proposed by Basile & De Benedictis (2007), who examined the relationship between regional unemployment and labour productivity in Europe. They employed the General Oligopolistic Equilibrium method, assuming that while each company is large within its industry, it remains infinitesimally small in the broader economy. Labour productivity is modelled by wages, occupational activity, market potential and labour market regulations. Their results indicated a non-linear negative relationship between labour productivity and regional unemployment. Konings and Marcolin (2014) also analyzed labour productivity on a microeconomic level, specifically in relation to wages. They assumed that labour markets are perfectly informed and capable of allocating workers whose salaries correspond to their marginal product of labour. The authors estimated both labour productivity function and a wage equation at Belgian firm level. The obtained results were coherent with the presence of institutional barriers to the adjustment of wages to labour productivity. Jarmołowicz and Kuźmar (2015) aimed to identify the fundamental mechanisms and relationships between the institutional environment and labour productivity. Their analysis of institutional diversity across selected European Union regions showed that effective institutional solutions have a significant impact on the development of labour productivity at the regional level. Similar findings on labour market policies impact on labour outcomes in OECD are obtained by Knapińska & Woźniak-Jasińska (2024). In this regard, the importance of distributive justice within institutional quality is proved by Mishchuk et al. (2019).

Lengyel and Eriksson (2016) examined the role of labour mobility, considering it not only as a driver of regional economic dynamics, but also a factor affecting productivity growth. The effect is ambiguous: while some companies benefit, other experience losses. However, the authors argued that co-worker networks formed through spatial labour mobility are crucial for both learning opportunities and job matching and thus should facilitate regional growth. Moreover, they demonstrated that an increase in co-worker network density is positively related to regional productivity growth. In turn, Christopoulos and Tsionas (2004) investigated the impact of technology gaps and capital-labour ratio growth on changes in labour productivity across Greek administrative territorial units from 1971 to 1995. The results showed that the capital-labour ratio plays a significant role in explaining regional productivity differences.

Herman (2020) analyzed changes in labour productivity in the Romanian manufacturing sector from 2008 to 2016, identifying a strong correlation between labour productivity and wages. The same effect is proved for Ukrainian enterprises (Mishchuk et al., 2021). In turn, Kekezi (2021) who studied the creative industries in Sweden, concluded that occupational experience diversity positively effects labour productivity, while the diversity of industry experience has a negative relationship with productivity.

Chugaievska, Filipowicz, Tokarski and Wisła (2020) developed a gravity model of economic growth for Ukraine. Their article assessed the impact of two economic aggregates-labour productivity and the capital-labour ratio-while considering their correlation with gravity effects. Their regression model explained labour productivity as a function of the capital-labour ratio, gravity effects and total factor productivity. The authors emphasized three key findings. First, the period from 2001 to 2008 was the most favourable period for the development of Ukrainian economy after the restoration of Ukraine's independence in 1991. Second, a scenario analysis indicates future strong position of Northern Ukraine (Kyiv city, Kyiv region with expected spillover effects). Third, implementation of solutions for equalization of regional investment rates in regional development policy could help minimize economic polarization in spatial terms by 2050.

Similarly, Filipowicz, Kelebaj and Tokarski (2023) examined spatial variations in labour productivity across Italy to identify their causes. To achieve this, they applied the gravity model of economic growth drawing from the Solow economic growth model. The principal finding concerned the relative impact of various factors on labour productivity, followed by differences in urbanization rates and regional and national gravity effects. Previously, Filipowicz, Tokarski and Wisła (2018) analyzed variations across European Union countries using the gravity growth model. Their projections suggested that, assuming sustained national investment rates from 2000-2015, 2000-2008 or 2009-2015 until 2050, post-communist economies would exhibit the highest annual average dynamics of changes in labour productivity compared to other analytic groups. Additionally, assuming an EU-wide investment rate in 2016-2050 similar to that of 2000-2015, 2000-2008 or 2009-2015, they hypothesized that labour productivity across the three largest country groups would converge by2050. This article, like the paper by Mroczek, Nowosad and Tokarski (2015), refers to and continues those studies.

2. Methodological approach

2.1. The gravity model

The gravity model is widely applied in international trade theory. Originally, the model was designed to explain trade volumes using such concepts as "mass" and "distance" between specific trading partners, which are directly derived from Newton's law of gravitation. The gravity model has proven to be an effective tool for explaining the factors that determine the demand structure in trade, leading to its continuous evolution (Klimczak, 2015, p. 108-111). In macro- and mesoeconomic modelling, "mass" is usually represented by a country's or region's GDP or population size. In turn, "distance" is commonly understood as the geographical distance between a country's most developed regions or between the capital cities of the studied countries. Consequently, the individual gravity effects analyzed in this article are described by the following equation:

$$\forall i, j \in G \wedge i \neq j \; g_{ij}(t) = \frac{k_i(t)k_j(t)}{d_{ij}^2(t)},$$

where $g_{ij}(t)$ is an individual gravity effect, $d_{ij}(t) > 0$ is the distance between country i (e,g. its capital city) and country j (its capital city), $k_i(t)$ is the capital-labour ratio in country i, and $k_j(t)$ is the capital-labour ratio in country j (Filipowicz et al., 2023). The model assumes that interaction occurs between a finite number of countries N ($N \geq 2$). This interaction is described by individual gravity effects. The set of N countries in which this interaction occurs is denoted by G (in the case of EU countries, G ={1, 2, …, 27}).

The gravity effect is thus directly proportional to the product of e.g. physical capital values or capital-labour ratios, which reflect the economic potentials of the respective countries. Conversely, the gravity effect is inversely proportional to the square of the geographical distance between those economies. The interpretation of this fact says that countries or smaller units located in close geographical proximity (the geographical distance is small which results in a greater quotient) exhibit stronger interactions compared to those situated at greater distances.

Individual gravity effects can be naturally extended to derive total gravity effects, which are defined as the geometric mean of individual gravity effects. They are thus given by the formula

$$g_{it} = k_{it} \prod_{j \neq i} \frac{k_{jt}^{1/(N-1)}}{d_{ij}^{2/(N-1)}} ,$$

where N is the number of regions analyzed, k_{it} is the capital-labour ratio in region i (as previously), k_{jt} is the capital-labour ratio in region j, while d_{ij} is the distance between region i (or its capital city) and region j (or its capital city).

In this article, the gravity effect is understood as total gravity effects as defined above.

2.2. Distance in the gravity model

Two key concepts underlying gravity theory are mass and distance. The first is characterized by economic, demographic or technological factors (Czarny, Folfas, 2011), while the other focuses on various relations occurring between objects. The concept of distance poses the greatest methodological challenge. An in-depth discussion on distance was initiated by J.E. Anderson and E. van Wincoop (2003, 2004), who synthesized and systematized previous research in this area. They presented a division of distance into four types: political, transfer, wholesale and retail distribution. They also proposed the concept of communication distance relating to speaking or not the same language. Other researchers have also examined communication and cultural barriers, developing more comprehensive measures for assessing distance (Melitz, 2008; Melitz and Toubal, 2012). Klimczak (2015), in turn, proposed additional variables such as political distance relating to the membership in trade organizations, customs unions or currency unions and historical distance, showing how a common history may determine current relations, based on historical colonial or warfare relations.

Researchers who use the gravity model of economic growth tend to less focus on defining an extensive set of distance-related variables. Instead, they adopt a single universal variable, namely the physical space between the capital cities of states or regions, characterizes the distance between the countries studied. The reason is that the states (regions, towns, centres) located close to their neighbours tend to experience higher growth rates due to faster and more cost-effective transfer of goods or of production factors. Tokarski, in his multiple studies (2014, 2015, 2018, 2023), defines distance as the space between the capital cities of regions measured in a straight-line along geographic coordinates using Pythagoras' theorem. While this simplification may be suitable for analyzing a single country, it becomes imprecise when applied to larger geographical entities such as the European Union, due to the Earth's curvature. To address this limitation, the authors of this article propose using the haversine formula to measure the distance between the capital cities of the selected countries.

The haversine formula stands for an equation that defines the distance between two points on a sphere, considering their longitudes and latitudes. The formula is particularly significant in navigation, where it determines the shortest distance between two locations on the Earth's surface, unaffected by variations in altitude or depth. It is also a special case of a more general formula in spherical trigonometry, which relates the sides and angles of spherical triangles (Azdy and Darnis, 2020, p. 3-4).

Importantly, this is still an approximation as Earth is certainly not a perfect sphere. However, the deviations introduced by this assumption are generally minor and can be considered negligible for more practical applications. Below, we present a mathematical perspective and application of the haversine formula in practice.

Let α be the central angle between two points on a spherical Earth. Then

$$\alpha = \frac{d}{r},$$

where d is the distance between two points measured along the great circle of the sphere (the great circle is the largest circle that can be drawn on a sphere; the equator is a special case of the great circle), r is the radius of the sphere.

The haversine formula for central angle α is given by the equation:

$$hav(\alpha) = hav(\varphi_2 - \varphi_1) + cos(\varphi_1)cos(\varphi_2)hav(\lambda_2 - \lambda_1),$$

where φ_1, φ_2 are geographical latitudes, and λ_2, λ_1 are geographical longitudes of the two selected points on a spherical Earth.

The formula given above may be transformed to obtain

$$hav(\alpha) = hav(\varphi_2 - \varphi_1) + (1 - hav(\varphi_1 - \varphi_2) - hav(\varphi_1 + \varphi_2)) \cdot hav(\lambda_2 - \lambda_1).$$

The haversine formula for angle α also equals

$$hav(\alpha) = sin^2\left(\frac{\alpha}{2}\right) = \frac{1 - cos(\alpha)}{2},$$

which results from elementary trigonometric transformations.

By transforming the equation given above using the original equation and the properties of the *arcus sinus* function, we obtain:

$$d = 2r \cdot arcsin(\sqrt{hav(\alpha)}),$$

and then:

$$\begin{aligned} d &= 2r \cdot arcsin\left(\sqrt{hav(\alpha)}\right) \\ &= 2r \cdot arcsin\left(\sqrt{hav(\phi_2 - \phi_1) + \left(1 - hav(\phi_1 - \phi_2) - hav(\phi_1 + \phi_2)\right) \cdot hav(\lambda_2 - \lambda_1)}\right) \\ &= 2r \\ &\cdot arcsin\left(\sqrt{sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \left(1 - sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) - sin^2\left(\frac{\phi_2 + \phi_1}{2}\right)\right) \cdot sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \\ &= 2r \cdot arcsin\left(\sqrt{sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + cos(\phi_1) \cdot cos(\phi_2) \cdot sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right), \end{aligned}$$

representing a maximum expansion of the equation using the formulas developed previously (Gade, 2010, p. 395-417).

2.3. Sources of data

Labour productivity was analyzed using its traditional definition, defined as the quotient of gross domestic product and the number of jobs. It is explained in terms of two variables, the capital-labour ratio and gravity effects. The study is based on data retrieved from the database kept by the UNECE (United Nations Economic Commission for Europe). All monetary values are presented in constant 2010 prices (discounted using the annual inflation rate). The analysis covers the years 2000-2021.

3. Spatial variations in labour productivity and its selected determinants

3.1. Labour productivity

Gross domestic product, at fixed prices (2010 = 100), grew at varying rates over the period under study. Ireland experienced the fastest growth (180% over 2000-2021). A group of countries that joined the EU after 2003, including Lithuania (125% growth in the period under analysis), Romania (116%), Poland (110%), Estonia (108%) and Slovakia (103%), followed. Slightly lower growth rates were observed in Latvia (94%) and Bulgaria (88%). In turn, Czechia (67%), Hungary (64%) and Slovenia (61%) exhibited distinctly lower growth rates. The largest European economies: Germany (25% growth) and France (26%) can attribute their results to the effect of a high base.

Italy's GDP growth over the 2000-2021 period was modest, at just 1%, while the Greek economy experienced zero growth. The economies of Austria, Belgium, Denmark, Finland or the Netherlands were characterized by an increase in GDP of approximately 30% over the last two decades.

Changes in the number of jobs during the analyzed period were more varied. Four countries experienced declines in the total number of jobs, with the largest drop observed in Romania (by 28%, i.e. about 3 million jobs), a smaller one in Latvia (by 7%, about 70 thousand jobs), in Portugal (by 2%, about 81 thousand jobs) and in Lithuania (by 1%, 17 thousand jobs). In contrast, the largest percentage increases in the number of jobs were observed in Luxembourg (by 84%, 223 thousand jobs), Malta (83%, 121 thousand jobs), Cyprus (42%, 133 thousand jobs) and in Ireland (41%, 693 thousand jobs). The considerable percentage changes can, to a significant extent, be attributed to the low base effect and the small populations of these countries. The greatest nominal increases in the number of jobs were observed in the largest European economies and the most populous states. The growth leaders include Germany (13%, 5 million jobs), Spain (20%, 3.3 million jobs) and France (12%, 3.1 million jobs). They are followed by Poland (15%, 2.1 million jobs) and the Netherlands (19%, 1.6 million jobs).

Labour productivity was calculated using its classical definition, i.e. the quotient of gross domestic product and the number of jobs. The most significant increases in labour productivity were observed in countries that experienced a decline in the number of jobs while maintaining stable GDP values, or in countries where GDP grew substantially with only moderate increases in the number or jobs. Romania is the growth leader with a 202% rise in labour productivity, followed by Latvia (127%) and Lithuania (110%). All countries were characterized by a fall in the number of jobs over the period under study. Countries where the number of jobs did not fall, and still a substantial rise in labour productivity was reported include: Ireland (98%), Estonia (90%), Poland (83%), Bulgaria (76%) and Slovakia (73%). Notably, those rises reached peaks both in their percentage and nominal (calculated at fixed prices) values (in descending order: 72.6 thousand USD, 32.3 thousand USD, 30.3 thousand USD, 18.9 thousand USD and 26.7 thousand USD). Among the largest European economies characterized by a stable increase in both GDP and the number of jobs over the years under analysis, also a steady rise in labour productivity was observed. It amounted to 11% (7.7 thousand USD) in Germany, 12% (9.2 thousand USD) in France, 7% (4.5 thousand USD) in Spain. A drop in productivity was observed in three countries. As regards Italy (-7%, -5.9 thousand USD) and Greece (-8%, -4.7 thousand USD), it resulted from an increase in the number of jobs alongside an almost zero GDP growth rate. However, Luxembourg (-7%, -9.3 thousand USD), which experienced substantial increase in GDP (71%), but also by a large increase in the number of jobs (84%).

3.2. Capital-labour ratio

No data on the value of physical capital were available in the sources, hence it was calculated based on capital expenditures on that resource. A general equation describing a rise in the capital stock is as follows:

$$\Delta K_{it} = I_{it} - \delta K_{it-1},$$

where ΔK_{it} is the change in physical capital over time, I_{it} represents capital expenditures on the stock of capital K_{it}, and δ is the depreciation rate of physical capital K_{it}, which is assumed to be 6%. This value is determined based on information provided by (Filipowicz et al., 2023) or (Mroczek and Tokarski, 2014), who estimate this indicator to be between 5% and 6%. Also a 10-year lag in capital modelling was assumed, and, consequently, data on capital expenditures was retrieved starting from 1990 to model physical capital as of 2000. A general formula describing physical capital in year *i* is an infinite sum of capital expenditures in that year and prior years, multiplied by the capital depreciation rate raised to the power representing the age of capital. In this article, a simplification is made to consider only 10-year periods (10-year sums), as shown in the following formula:

$$K_{it} = \sum_{i=1}^{\infty}(1-\delta)^{i-1}I_{t-i} \approx \sum_{i=1}^{10}(1-\delta)^{i-1}I_{t-1}.$$

The capital-labour ratio was then determined for each year under study. Similar to labour productivity, the largest increases in capital-labour ratio were reported in countries that reduced their number or jobs. A 287% increase was observed in Romania, a 261% increase in Lithuania, and a 192% increase in Latvia. Similarly large increased in the capital-labour ratio were recorded in Bulgaria (288%), Estonia (203%) and Ireland (192%). Four countries reported a decline in the value discussed. These include Greece (-33%), Cyprus (-12%), Portugal (-8%) and Italy (-7%). As for Cyprus and Italy, drops in the capital-labour ratio were caused by an increase in the number of jobs that overtook the increase in capital value, since the difference in that variable (calculated at fixed prices) was positive between 2021 and 2000. However, Greece reported both a decline in the capital value and a rise in the number of jobs which translated into the greatest drop in the capital-labour ratio among the countries under study. Portugal, in turn, reported both a decline in total capital and a drop in the number of jobs. The strongest European economies were characterized by a stable and relatively similar increase in the capital-labour ratio: Germany reported a 10% increase, France a 29% increase, Spain a 12% increase, the Netherlands a 18% increase.

4. Conducting research and results

4.1. The regression model with gravity effects

In the first phase, the linear regression model took the following form:

$$\ln y_{it} = \alpha_0 + \alpha_1 \ln g_{it}, \quad (1)$$

where y_{it} is labour productivity in year *t* in country *i* (t=2000,…,2021), g_{it} is the gravity effect in year *t* in country i, and α_0, α_1 are constants.

Model 1: KMNK estimation, observations used 1-594

Dependent variable (Y): ln_y

	Coefficient	*Stand. error*	*Student's t*	*p value*	
const	5.20135	0.0790172	65.83	<0.0001	***
ln_g	0.204914	0.0154735	13.24	<0.0001	***

Depend.var.arithm.mean	4.165008	Depend.var.stand.dev.	0.303293
Residual sum of squares	42.08167	Residual stand. error	0.266616
Coeff. of determ. R squared	0.228539	Adjusted R squared	0.227236
F(1, 592)	175.3751	p value for F test	3.01e-35
Log likelihood	-56.61118	Akaike inform. crit.	117.2224
Schwarz bayes. crit.	125.9961	Hannan-Quinn crit.	120.6394

Source: own studies using the gretl statistical package

The results presented in the table above lead to the conclusion that the model is statistically significant, as demonstrated by the significance (p.value) of less than 0.0001 for the selected exogenous variable (the gravity effect). Moreover, that variable has a positive effect on endogenous labour productivity (the regression model coefficient is 0.205). Additionally, the p.value for F-test is 3.01e^(-35), which indicates high predictive capacity of the regression model, thus confirming that the regression coefficient in the model is significantly different from 0. R-squared value has a relatively satisfactory value (gravity effects explain about 23% of variation in labour productivity). It is then assumed that elasticity y relative to g is 0.205. Thus, given the variable:

$$ln\, f_{it} := ln\, y_{it} - 0.205\, ln\, g_{it}, \quad (2)$$

the parameters are estimated in equation:

$$\ln f_{it} = a_0 + \mathrm{FE} + a_1 \ln k_{it}, \quad (3)$$

where k_{it} is capital in country *t* and year *i*, and FE is fixed effects.

Model 2: KMNK estimation, observations used 1-594
Dependent variable (Y): ln_f

	Coefficient	*Stand. error*	*Student's t*	*p value*	
const	4.51471	0.0653493	69.09	<0.0001	***
d_Austria	-0.214798	0.0208202	-10.32	<0.0001	***
d_Belgium	-0.0503722	0.0208516	-2.416	0.0160	**
d_Bulgaria	-0.483599	0.0251983	-19.19	<0.0001	***
d_Croatia	-0.465173	0.0219630	-21.18	<0.0001	***
d_Cyprus	0.119917	0.0211648	5.666	<0.0001	***
d_Czechia	-0.506500	0.0210516	-24.06	<0.0001	***
d_Denmark	-0.0719309	0.0209350	-3.436	0.0006	***
d_Estonia	-0.307278	0.0214812	-14.30	<0.0001	***
d_Finland	-0.0406761	0.0208049	-1.955	0.0511	*
d_France	-0.0612163	0.0207934	-2.944	0.0034	***
d_Germany	-0.193673	0.0209384	-9.250	<0.0001	***
d_Greece	-0.0209355	0.0216026	-0.9691	0.3329	
d_Hungary	-0.413750	0.0218581	-18.93	<0.0001	***
d_Ireland	0.215399	0.0208107	10.35	<0.0001	***
d_Italy	-0.0802583	0.0208489	-3.850	0.0001	***
d_Latvia	-0.340214	0.0223007	-15.26	<0.0001	***
d_Lithuania	-0.254886	0.0229965	-11.08	<0.0001	***
d_Luxembourg	0.241019	0.0208898	11.54	<0.0001	***
d_Malta	0.0869158	0.0212905	4.082	<0.0001	***
d_Netherlands	-0.0765079	0.0208040	-3.678	0.0003	***
d_Poland	-0.326875	0.0227983	-14.34	<0.0001	***
d_Portugal	-0.0285045	0.0214901	-1.326	0.1852	
d_Romania	-0.391885	0.0227361	-17.24	<0.0001	***
d_Slovakia	-0.408626	0.0215407	-18.97	<0.0001	***
d_Slovenia	-0.356630	0.0210904	-16.91	<0.0001	***
d_Spain	0.0343696	0.0208230	1.651	0.0994	*
ln_k	0.186540	0.0131169	14.22	<0.0001	***

Depend.var.arithm.mean	5.201786	Depend.var.stand.dev.	0.266391
Residual sum of squares	2.691885	Residual stand. error	0.068964
Coeff. of determ. R squared	0.936032	Adjusted R squared	0.932980
F(27, 566)	306.7466	p value for F test	0.000000
Log likelihood	759.9519	Akaike inform. crit.	-1463.904
Schwarz bayes. crit.	-1341.071	Hannan-Quinn crit.	-1416.066

Source: own studies using the gretl statistical package

The form of a finally calibrated equation:

$$ln\, y_{it} = 4.515 + FE + 0.205\, ln\, g_{it} + 0.187\ \ ln\, k_{it}. \tag{4}$$

The values presented in the table above and the final calibrated equation lead to the following conclusions. The capital labour-ratio is statistically significant (p.value < 0.0001) and has a positive effect on labour productivity (the regression model coefficient is 0.187). Furthermore, the p.value for F-test is close to zero, which indicates a high predictive capacity of the regression model; thus the regression coefficient in the model is significantly different from 0. Adjusted R-squared value is close to 1 (the exogenous variable: capital labour-ratio explains about 93% of the variation in the endogenous variable: labour productivity). Fixed effects (FE) are statistically significant for a substantial majority of countries (p.value < 0.0001). Only Greece and Portugal are marked as statistically insignificant (0.33 and 0.19, respectively), while for Belgium and France the values fall within the range between 0.05 and 0.1. However, considering the large number of countries under study, this has a negligible effect on the model. The final calibrated equation in its form given above also includes gravity effects, which have a positive effect on labour productivity (the coefficient is 0.205).

5. Discussion and limitation

An apparent limitation lies in the dual use of the variable representing the capital labour-ratio, both as an independent exogenous variable and indirectly in the definition of total gravity effects. From the perspective of analysis conducted , this is not an error. Reasons are provided through the following simple transformations. It is sufficient to consider the labour productivity function described by the formula:

$$y_j(t) = g_j^{\beta}(t) k_j^{\alpha}(t), \tag{5}$$

where y_j is the level of labour productivity in region j, g_j represents the total gravity effects influencing region j, k_j is the capital-labour ratio in region j, and $\alpha, \beta \in (0,1)$ are elasticities of labour productivity relative to the capital-labour ratio and total gravity effects, respectively. Total gravity effects are given by the following formula:

$$g_j(t) := k_j(t) \prod_{j \neq i} \frac{k_i(t)}{\bar{d}_j}, \tag{6}$$

where $\bar{d}_j$ is the geometric mean distance between region j (or its capital city) and other regions (or their capital cities), with the remaining symbols as previously defined. Let γ_j denote the product of individual quotients given above, i.e.

$$\gamma_j(t) := \prod_{j \neq i} \frac{k_i(t)}{\bar{d}_j}. \tag{7}$$

Then, certainly $g_j(t) = k_j(t)\gamma_j(t)$ and $y_j(t) = \gamma_j(t)^{\beta} k_j^{\alpha+\beta}(t)$. By applying natural logarithm to the second equation, we obtain the following equation

$$ln y_j(t) = \beta ln \gamma_j(t) + (\alpha + \beta) ln k_j(t). \tag{8}$$

The use of the gravity model in the analysis may be debatable, because (as previously indicated) the model was originally applied in the theory of trade. However, it should be emphasized that the gravity model of economic growth, by its structure, draws from the Solow economic growth model, complementing it with the factor of total gravity effects. As noted earlier, this article continues the research initiated by Mroczek, Nowosad and Tokarski (2015).

Certainly, a limitation to further study lies in the method used to determine physical capital. This results from the absence of data on the gross value of property, plant, equipment in publicly available databases. It would be beneficial to identify physical capital precisely, aligning it with that category of resources, rather than using capital expenditures, which represent a flow. In this article, we assumed a capital depreciation rate equal 6%, and a 10-year lag in modelling physical capital, which consequently shorted the period available for analysis.

6. Conclusion and summary

The analysis of the relationship between labour productivity, physical capital and total gravity effects confirms the proposed hypotheses. A higher level of the capital labour-ratio significantly contributes to the growth in labour productivity. Similarly, a correlation was demonstrated: a greater geometric mean of the squares of the distances between the capital cities of countries has a negative effect on labour productivity. This is confirmed by the coefficients in the final equation (4) above, where the coefficient for the natural logarithm of total gravity effects equals 0.205 and for capital labour-ratio equals 0.187.

The results obtained are consistent with existing literature. The effect of physical capital on labour productivity has also been demonstrated by: Christopoulos, Tsionas (2004); Chugaievska, Filipowicz, Tokarski, Wisła (2020) and Filipowicz, Tokarski, Kelebaj (2023). Research into the influence of gravity effects on labour productivity is currently being developed (Filipowicz et al., 2018). The category of distance in the gravity model remains an open question. The model, in its original form, was used in trade theories that proposed diverse definitions of distance, ranging from political and transfer distance to wholesale and retail distribution distance. In the existing meso- and macroeconomic studies on labour productivity, distance is typically measured as the physical space between the capital cities of regions under analysis. This is often dramatically simplified, using Pythagoras' theorem, The unique approach presented by the authors of this article is based on the use of the haversine formula that determines the distance between two points on Earth, considering its spherical shape.

The confirmed hypotheses are also supported by intuition. A smaller distance between the capital cities of regions promotes their dynamic growth by facilitating faster and cheaper exchange of goods and production factors. In turn, a greater value of the capital labour-ratio positively affects the rate of labour productivity.

With regards to the practical value of the research, the main aim was to capture relationship between labour productivity, gravity effects and capital-labour ratio. Research shows that countries with lower economic potential but located closer to each other may interact more strongly than countries with higher economic potential but located far from neighbours. That interaction improves labour productivity. Authors are aware that chance for changing distance between European Union countries capitals is close to zero. But other solutions may be performed, including more investments in capital to balance negative effects of distance.

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