The Socio-Economic Regionalisation and the Administrative Division of Ukraine Through the Lens of the Gravity Model

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Abstract

The paper explores the application of the gravity model, namely the delineation of the urban predominant influence areas via the generation of the multiplicatively weighted Voronoi diagram, to the socio-economic regionalisation and administrative territorial division of Ukraine, including the existing state of affairs and several proposals on their improvement. The research uses quantitative statistical data on interregional migration and rail passenger traffic within the country, processed via the Statistica analytics software, and a subsequent spatial analysis conducted by GIS. The findings suggest that the gravity model can serve as a tool for optimisation the administrative territorial division, as well as for the delineation of the planning regions and urban hinterlands. At the same time, it has certain limitations and should not be treated as a panacea for regional planning and development.

Keywords

gravity model, multiplicatively weighted Voronoi diagram, spatial planning, regionalisation, administrative division, Ukraine

Introduction

Gravity models are well-known in geography and have been employed for simulation and forecasting of various spatial interactions since the middle of the 20th century. In human geography, they have been employed for the delineation of urban spheres of influence/urban planning regions since 1970s (Huff, 1973; Berry & Lamb, 1974). In recent decades, gravity models in their various modifications have been used for different purposes. For instance, the list of possible applications includes studies of urban hierarchies and regionalisation (Mu & Wang, 2006), transportation (Cordera et al., 2018), logistics (Galvão et al., 2006; Riol et al., 2011), migration (Pietrzak et al., 2013; Ramos, 2016), commuting (Stefanouli & Polyzos, 2017), international trade (e.g. Kahane, 2013; Salvatici, 2013; Shepherd, 2013; Nijkamp & Ratajczak, 2021), mail and telephone communication (e.g. Dodd, 1950; Krings et al., 2009), measuring consumer preferences (Boots and South 1997), predicting administrative boundaries between settlements (Wilebore & Coomes, 2016), and identifying farmers' daily life circles (Tian et al., 2018).

Nevertheless, in Ukraine, to the best of our knowledge, gravity models, in particular the multiplicatively weighted Voronoi diagram, have never been used for the purpose of regional administration, planning, and development. The only exception was application of weight coefficients to the simple Voronoi diagram in order to delineate the spheres of influence for six Ukrainian largest cities (Mezentsev, 2005).

In 2020, Ukraine completed the administrative division reform, establishing a network of new amalgamated *raions* (districts) and *hromadas* (territorial communities) (Horbliuk & Brovko, 2022; Kaliuzhnyj et al., 2022). The shortcomings of the spatial configuration of the newly established administrative units in Ukraine have been discussed in the literature (Udovychenko et al., 2017; Baranovskyi, 2020; Makarov & Duda, 2021). In addition to the other critical comments put to administrative-territorial division, the socio-economic capability of new administrative centres is questioned. A question arises: to what extent are the new administrative centres of *raions* and territorial communities able to fulfil the role of centres of socio-economic gravity for their administrative units? *Oblasts* (regions), the first-order administrative units of Ukraine, inherited from the Soviet era, are listed in the Ukrainian Constitution and have been kept untouched to date. Nevertheless, occasionally, proposals are made regarding the need to adjust the borders of oblasts or to radically change the whole network of the oblasts (e.g. the establishment of new oblasts or re-establishment of some oblasts cancelled once in the past). How feasible are these proposals from the point of view of the socio-economic gravity of the surrounding regions to the existing and proposed oblast capitals? Finally, in Ukraine, there are different schemes of socio-economic regionalisation, including one with the official status – The General Scheme of Planning of the Territory of Ukraine. Which of them are more reliable and better describe the factual patterns of spatial interaction? Testing the gravity model on the example of different types of urban centres in Ukraine, this paper aims to answer the aforementioned questions. On the other hand, this paper pursues a task to check the gravity model itself, comparing the modelling results with well-known spatial patterns.

The remaining part of the article is organised as follows. The next section briefly describes the theoretical basics of the gravity model in geography. Thereafter, the research methodology and data are presented. The following sections outline the modelling results in relation to the socio-economic regionalisation of Ukraine, the division of Ukraine into oblasts (first-order administrative units), and the network of the newly established *raions* (second-order administrative units). The final section draws key concluding remarks.

The gravity model and socio-economic regionalisation

According to the first law of geography (Tobler, 1970; 2004) “everything is related to everything else, but near things are more related than distant things”. The second law of geography, proposed by Arbia et al. (1996), asserts that “everything is related to everything else, but things observed at a coarse spatial resolution are more related than things observed at a finer resolution”. In this way, the first law reflects the inverse proportional relation between the spatial interaction and distance, while the second law insists on the direct proportional relation between the spatial interaction and the size of a place (Chen, 2015). Finally, the environment of the interacting places affects the speed of interaction and the level of its decay with a distance. The spatial interaction of places is understood as a broad phrase encompassing any movement over space that results from a human activity (Haynes & Fotheringham, 1985).

Based on the aforementioned assumptions, it is possible to provide a quantitative estimate for the spatial interaction of two places. In the simplest form, the gravity model appears as follows:

$$F = K \frac{M_i M_j}{D_{ij}^{\beta}} \tag{1}$$

where F is a “force” (intensity) of interaction of two geographical places, M_i and M_j are “masses” (sizes) of interacting places i and j, D is a distance between the interacting places, K is a linear proportionality constant, and power function β is a friction of distance coefficient.

In order to enhance the precision of the assessment, the gravity model has been subjected to further modifications and amendments. In particular, a more complex model for single-direction interaction, derived from Alonso’s general theory of movement (Alonso 1976), was proposed to control for a possible nonlinearity of the mass effect of places on the interaction:

$$T = K \frac{M_i^{\alpha 1} M_j^{\alpha 2}}{D_{ij}^{\beta}} \tag{2}$$

where T is a flow from a place i to place j, α_1 is an emissivity coefficient (a potential to generate movements), α_2 is an attractiveness coefficient (a potential to attract movements), M, D, and β refer to the variables previously discussed.

The idea of the standard potential of influence directly follows from the gravity model. It was first proposed by Stewart (1948), although shares the same underlying idea with the Reilly's law of retail gravitation (Reilly, 1931). In the post-Soviet countries, the standard potential model is often referred to as the Clark-Medvedkov model (Clark, 1951; Medvedkov, 1965, 1967). The potential of a place i at a given point j is equal to the ratio of the place size M to the distance D between them raised to the power of β, multiplied by proportionality constant K:

$$P = K \frac{M_i}{D_{ij}^{\beta}} \tag{3}$$

The main potential for a given point j is defined as the largest of all individual potentials of other places i that may influence a place located in the point j (individual potentials are calculated according to the formula 3):

$$P_{main} = MaxP(M_i, D_{ij}) \tag{4}$$

The area where the potential of a given place exceeds the potential of any other place can be defined as the predominant influence area (PIA) of that place. (In the literature, PIA of a city is commonly referred to as an urban sphere of influence, although this term is not entirely correct – the actual urban influence may spread far beyond this area; we are talking about the relative influence in comparison with the other defined set of cities). Given formulas 1 and 3, this means that any place within the PIA will interact more strongly with a given place than with any other place. The total pattern of PIAs for multiply places represents the multiplicatively weighted Voronoi diagram, also called circular Dirichlet tessellation (Ash & Bolker, 1986; Okabe et al., 2000).

The first use of the gravity model for the delineation of the US planning regions on the basis of urban spheres of influence was undertaken by Huff (1973), who argued that the regions achieved according to the model would be more suitable for various federal programmes than a traditional regionalisation highly influenced by political issues. Berry and Lamb (1974) used data on newspaper market circulation in the USA to assess the validity of using interaction models as a basis for measuring urban spheres of influence and, thereby, delineating planning regions. More recently, the multiplicatively weighted Voronoi diagram, built on the basis of demographic data, was found to be effective for studying spatial patterns of the US urban hierarchy, especially visualising theoretical regions delineated by socio-economic variables, with notable overwhelming influence from huge metropolitan areas (Mu & Wang, 2007). Deng et al. (2010), applying, in fact, a variety of the gravity model, identified urban spheres of influence for 168 cities in Central China. Guo et al. (2021) analysed a provincial division of economic zone in Hunan Province, China, via considering spatial interaction among regions based on the improved gravity model and clustering approaches. They found the proposed analytical framework to be of great potential in regional planning, and recommended to incorporate it to the toolkit of regional policy and sustainable development for local governments.

Moving to Europe, longitudinal study of the urban spheres of influence in Ireland (Huff & Lutz, 1995) indicated that new urban centres in the upper tiers of the urban hierarchy developed in areas where the hinterlands of the older centres in that tier had previously converged. Thus, the analysis of urban spheres of influences can be used as an important aid for government planning. Śleszyński (2015) employed gravity models to show the possibilities for administrative division optimisation in Poland. The author argued that the determination of the number of administrative units and their delimitation can be based on taking into account the natural attraction to large settlement centres, the intensity of which is estimated on the basis of measurable socio-economic interactions. The presence of an objective socio-economic attraction can contribute to greater spatial and functional cohesion, as well as a synergistic benefit from cooperation. In particular, based on the modelling results, he proposed two options of a more justified territorial division of Poland via increasing or reducing a current number of voivodeships (first-order administrative regions).

Kraft and Blažek (2012) applied gravity models to spatial interactions and the regionalisation of the Vysočina Region, the Czech Republic. They found that spheres of urban influence delineated with the gravity model show good correlation with a pattern of commuting. At the same time, contrary to Śleszyński (2015) and despite the still good correlation between the gravity model and the actual administrative division, they point out that the gravity model is rather inappropriate for designing a new administrative division or criticising the existing one. According to Kraft and Blažek (2012), the gravity model should be viewed as an appropriate tool rather than an absolute result of the entire research process.

The application of the gravity model to Ukrainian urban centres

Multiplicatively weighted Voronoi diagrams, reflecting the spatial shapes of urban PIAs, were built for Ukrainian urban centres of different hierarchical levels:

(1) for the key metropolises: Kyiv, Kharkiv, Dnipro, Odesa, Donetsk, Lviv (n = 6);

(2) for the oblast centres and other cities with a population over 100,000 (n = 44);

(3) for all cities and townships meeting the following conditions: population > 10,000 and/or administrative centres of *raions* (n = 396).

A regular network of points with a fixed step (5.00 km for n = 6 and n = 44, 1.97 km for n = 396) was constructed for the entire territory of Ukraine. For each point, the influence potentials of all cities, taken into account at the given stage of analysis, were calculated according to the formula (3). The population of the cities was taken for January 1, 2021 (State Statistics Service of Ukraine, 2021), and the straight line (geodesic) distance was employed for calculation. Then, each point was assigned an identifier of the corresponding city with the maximum influence potential according to the formula (4). The set of points with the same city identifier were coloured in the same colour, visualising in this way the PIAs of the corresponding cities. The procedures were performed using the QGIS 3.16 software.

To estimate the actual value of the friction of distance coefficient *β*, we calibrated the gravity model (formula 2), writing it in logarithmic form with subsequent linear regression analysis using the Statistica 7 software:

$$lnT = lnK + \alpha_1 lnM_i + \alpha_2 lnM_j + \frac{1}{\beta} lnD_{ij} \quad (5)$$

We used two datasets, reflecting two different types of spatial interaction, for the calibration procedure. The first dataset is interregional migration for 2010–2013 (State Statistics Service of Ukraine, 2021). This model reflects long-term migrations within the country. In total, we considered officially registered migrations between 26 Ukrainian first-order administrative regions, including 25 oblasts and the city-region of Sevastopol (the data on Kyiv, also having a status of a city-region, was merged with data on the Kyiv oblast). In this case, T is a number of migrants from the region i to the region j, M_i and M_j are populations of the regions i and j, D is a geodesic distance between the administrative centres of the regions i and j. Here, migration figures for the whole regions (oblasts) were attributed to their administrative centres, being in all cases their largest cities, and in most cases located not far from the geometric centre of the region. Such a simplification made it possible to work with available statistical data, but at the same time represent a methodological limitation (e.g. there is a risk of larger errors due to close flows in cross-border zones of the regions). The second dataset is rail passenger traffic from January 2014 to September 2015 (Texty, 2015). This model reflects primarily short-term mobility of Ukrainians. The cities of the war-affected Donetsk and Luhansk oblasts, as well as of the annexed Crimea, were excluded from the analysis. In this case, T is a number of passengers travelling from the settlement i to the settlement j, M_i and M_j are populations of the settlements i and j, D is a shortest railway distance between the settlements i and j.

Table 1. Calibration results for gravity models

Parameters	Model 1: Intraregional migration	Model 2.1: Railway passenger traffic	Model 2.2: Railway passenger traffic
α_1	1.04	0.47	–
α_2	0.96	0.46	–
β	1.37	0.23	0.92
lnK	–15.23	–0.52	–9.32
R	0.89	0.68	0.45
adj. R2	0.79	0.47	0.20

Source: Own elaboration.

The results of model calibration are presented in Table 1. For model 1 (intraregional migration), we found $\beta = 1.37$, while $\alpha_1 \approx \alpha_2$ and their values are symmetric with respect to 0. This indicated practically linear relationship between the regional population size and the emissivity/attractivity of the region for migrants. Thus, we may put $\alpha_1 = \alpha_2 = 1$. Interestingly, similar value for friction of distance ($\beta \approx 1.5$) was observed for intraregional migration in Poland (Pietrzak et al., 2013), although that research involved somewhat different methodology.

For the model 2.1 (railway passenger traffic), $\beta = 0.23$, while $\alpha_1 \approx \alpha_2 \approx 0.465$. In order to simplify the construction of PIAs and correctly compare the friction of distance coefficients for both types of migrations, we recalibrated the model putting $\alpha_1 = \alpha_2 = 1$. According to the received model 2.2, $\beta = 0.92$. The model for railway passenger traffic expectedly has worse predictive power than model for intraregional migration (see *R* and *adjusted* R^2 values for three models), since the constant population of a settlement is not always an adequate quantitative measure of railway passenger traffic. In particular, railway stations may accumulate passengers from the surrounding region; railway junctions in small towns that function as transfer stations may have disproportionately high passenger traffic; resorts and tourist centres have the bulk of passenger traffic formed by tourists and vacationers. Anyway, the lower value of β for railway passenger traffic compared to intraregional migration expectably means that permanent transfers are more confined to the neighbouring regions then short-term trips.

Even having these two calibrations, we cannot be sure that the calibrated values of β for two specific spatial interactions reflect the whole complex of spatial relationships. It is known that in human geography, expert estimates are often no less precise than mathematical modelling. Thus, additionally, we showed multiplicatively weighted Voronoi diagrams built for the oblast centres and other cities with a population of over 100,000 (n = 44; for $\beta \approx 0.5$, *1.0*, *1.5*, *2.0, 2.5*, *3.0*, *3.5*, *4.0*) to 30 local human-geography experts from different Ukrainian regions to estimate the most reliable actual value of β based on their personal experience and knowledge on regional geography. The most frequent answer (80%) was that $\beta \approx 2.5$. It should be noted here that the similar values of β (in a range from *2.0* to *3.0)* appeared to be reliably describing the PIAs of largest cities in Poland and thus applicable to the analysis of the first-order administrative units, namely voivodeships (Śleszyński, 2015), which are comparable in area and population to Ukrainian oblasts.

Therefore, finally, we built and analysed multiplicatively weighted Voronoi diagrams for three values of β: *0.92* (model calibration for railway passenger traffic), *1.37* (model calibration for intraregional migration), and *2.50* (expert estimations).

It should be emphasised that the simulation presented in the article was made for the whole state territory of Ukraine under pre-war conditions. In order to reflect the current changing patterns of the population after the beginning of the hybrid Russo-Ukrainian warfare in 2014, and especially after the beginning of the full-scale Russian invasion into Ukraine in 2022, the model should be recalculated using the actual data on population distribution and mobility/migration patterns.

Modelling results and socio-economic regionalisation

The existing schemes of the socio-economic regionalisation of Ukraine can be divided into two categories:

1. The first category of schemes is based on the criteria of the socio-economic gravity to a powerful centre – a city with metropolitan functions, which close on themselves spatial functional connections (Shablii, 1996; Palamarchuk & Palamarchuk, 1996; Dolishnii et al., 1997). The authors of these schemes have a consensus about the six metropolitan urban centres constituting the regional cores. However, there are different opinions as to how administrative oblasts should be divided between these gravity centres (Figures 1a, 1b);

2. The second category of schemes additionally accounts for regional economic profiles, and also identifies some smaller cities as promising gravity centres for planning purposes in the future (e.g. Popovkin, 1993; Nudelman, 2003; Pistun et al., 2004; Zastavnyi, 2010). Such schemes typically include a larger number of regions, and their average areas and populations are smaller compared to the regions from the schemes of the first category. For instance, these schemes often include regions without a clear single urban centre: the Podolian region (the *Vinnytska*, *Khmelnytska*, and *Ternopilska* oblasts), the North-West region (the *Volynska* and *Rivnenska* oblasts), the Central region (the *Cherkaska* and *Kirovohradska* oblasts) (Figures 1c, 1d). One of these schemes (Nudelman, 2003) has been used for the General Scheme of Planning of the Territory of Ukraine (effective in 2002–2020).

The gravity model confirms that six metropolises (Kyiv, Kharkiv, Dnipro, Odesa, Donetsk, and Lviv) can really play a role of gravity centres for their socio-economic regions (Figures 2a, 2b, 2c). The modelling results support more the scheme by Dolishnii et al. (1997), attributing the *Khmelnytska* oblast to the Kyiv's PIA (Figure 1b), compared to the scheme by Shablii, attributing it to the Lviv's PIA (Figure 1a). Moreover, according to the model, especially with low values of β, Kyiv's PIA extends far beyond to the west, partially covering oblasts typically included into the Western, i.e. Lviv's socio-economic region (the *Rivnenska*, *Ternopilska*, *Volynska*, *Chernivetska* oblasts). However, in real life, these oblasts of the western Ukraine may have closer ties with Lviv compared to Kyiv due to the common cultural traits and historical past. The gravity model, putting the *Kirovohradska* oblast mostly into the Kyiv's PIA, contradicts both these schemes, attributing this oblast to the region with a centre in Dnipro. Also, the gravity model indicates that although the *Poltavska* and *Sumska* oblasts in general gravitate to Kharkiv (constituting together the North-Eastern socio-economic region), their western parts are linked more to Kyiv than to Kharkiv. Also, the eastern part of the Khersonska oblast gravitates more to Dnipro than to Odesa, while the eastern part of the *Zaporizka* oblast gravitates more to Donetsk than Dnipro. Nevertheless, since socio-economic regions include administrative units in their entirety; the regionalisation schemes by Shablii (1996) and, especially, Dolishnii et al. (1997), generally fit well with the gravity model, especially in the case of $\beta = 2{,}5$.

With regard to the regionalisation schemes of the second category, according to the gravity model, the principal urban centres of the additional 'prospective' regions (e.g. Vinnytsia, Khmelnytskyi and Ternopil in the Podolian region, Lutsk and Rivne in the North-Western region, Cherkasy and Kropyvnytskyi in the Central region) cannot compete in spatial influence with the six aforementioned metropolises and are not able to cover with their PIAs the whole areas of their socio-economic regions. Of course, this does not mean that this type of schemes is not useful for regional development and planning; however, the respective socio-economic regions can hardly be considered as functional unities, and different parts of their areas are, in fact, gravitating to different urban metropolitan centres. Nevertheless, the historical retrospective of the spatial configuration of the first-order administrative units in Ukraine (Gnatiuk & Melnychuk, 2020), which generally correlates with gravity modelling presented in this article, shows that the 'Podolian' (roughly corresponding to the *Khmelnytska* and *Vinnytska* oblasts) and 'Volhynian' (corresponding to the *Volynska* and *Rivnenska* oblasts) regions tended to exist as separate administrative units from Kyiv. This means that unaccounted factors such as economic specialisation, historical memory, or cultural ties may be no less important for shaping persistent urban spheres of influence than socio-economic gravity to the large urban centres.

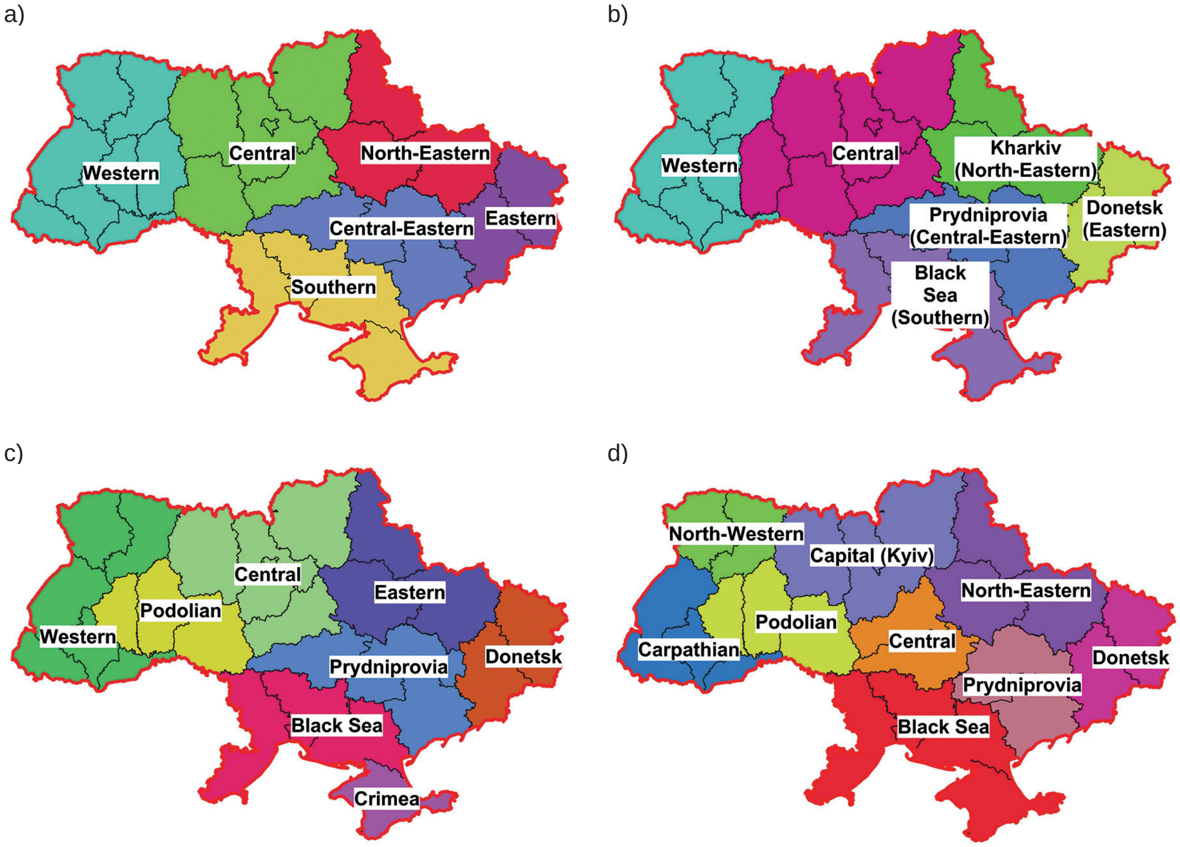


Figure 1. Examples of schemes of socio-economic regionalisation of Ukraine

Source: Elaboration based on: a) Shablii (1966); b) Dolishnii et al. (1977); c) Nudelman (2003); d) Pistun et al. (2004).

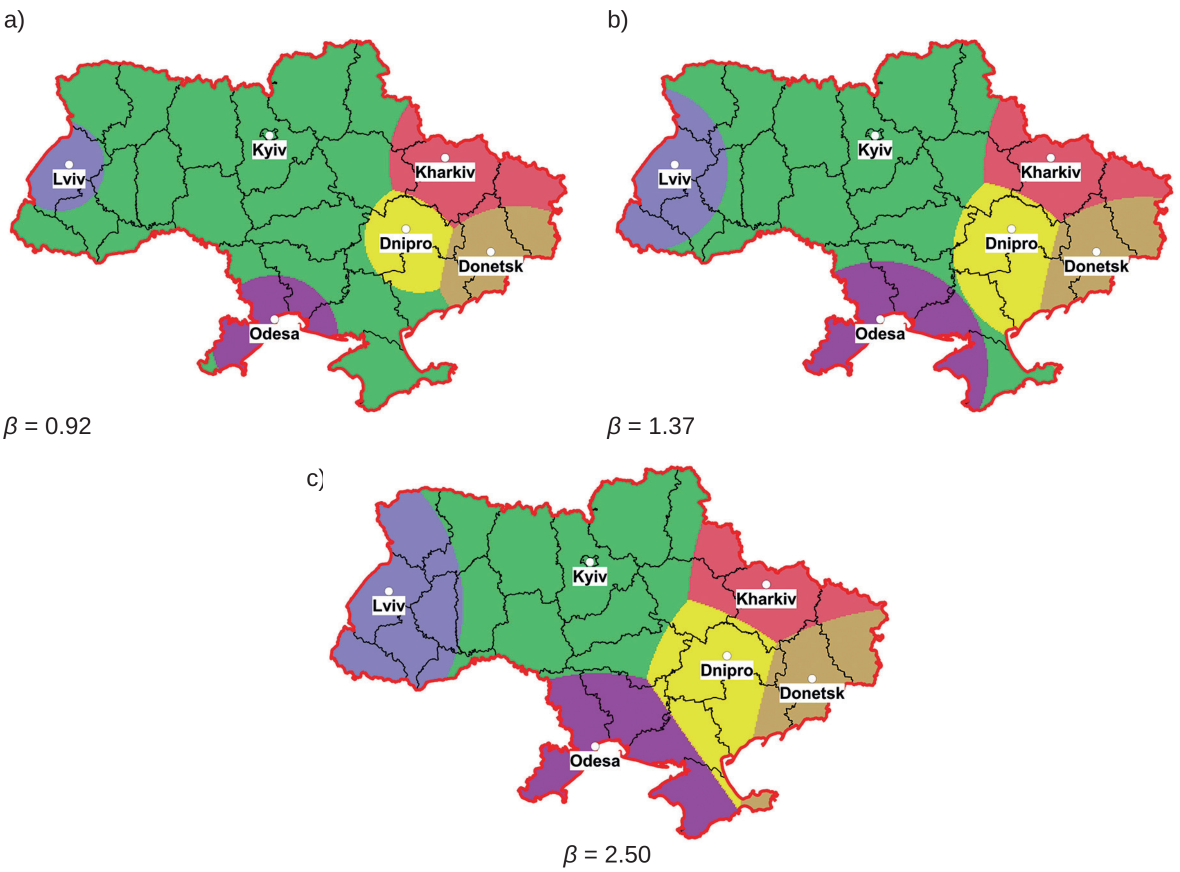


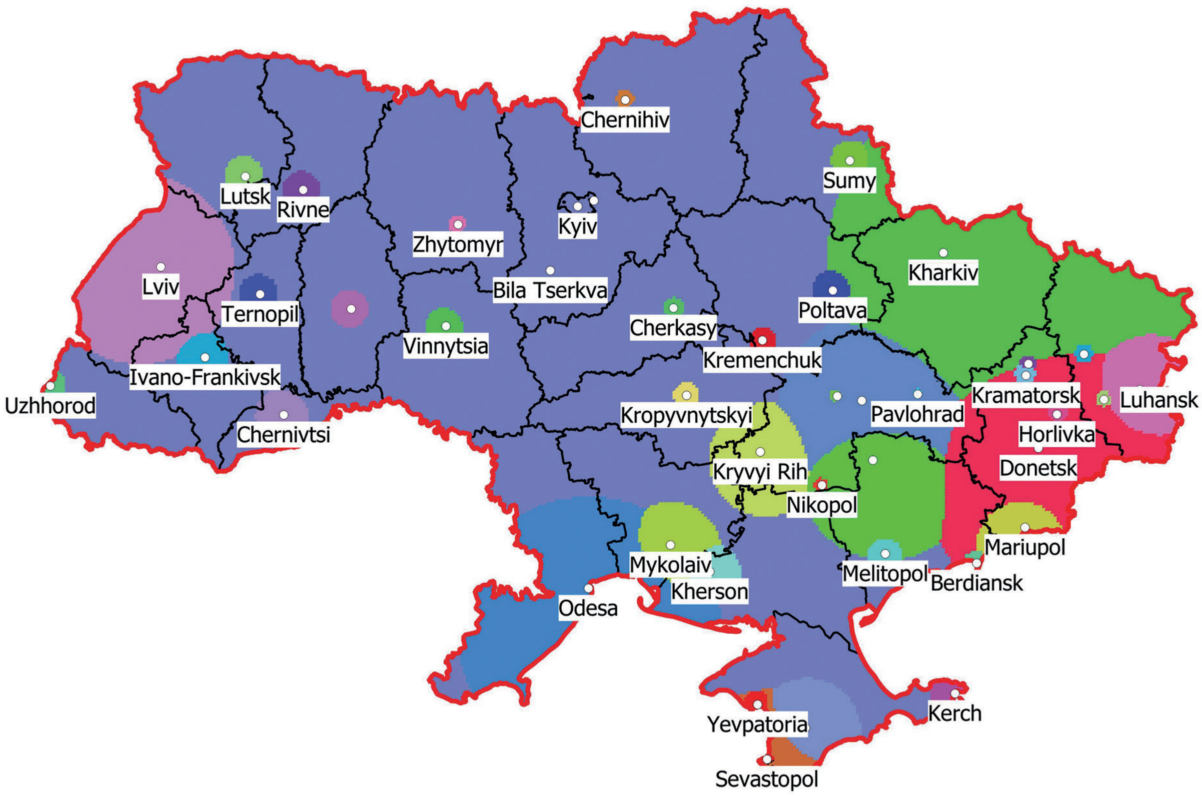
Figure 2. Predominant influence areas for the key six Ukrainian metropolises

Source: Own elaboration.

Modelling results and first-order administrative units (oblasts)

Modelling shows that the PIAs of many oblast centres do not cover the entire territory of their oblasts (Figures 3a, 3b, 3c). This applies particularly to the central and partly western part of Ukraine. This is explained by the powerful influence of Kyiv, the Ukrainian capital and the largest national metropolis, which is rivalled only by Lviv, and then only with relatively high values of the friction of distance coefficient. This is especially true for the oblasts directly adjacent to the *Kyivska* oblast. In particular, Zhytomyr and Chernihiv control the smallest proportions of their oblasts (in the best case, with $\beta = 2.5$, these figures are 37.0% and 34.2%, respectively) (Table 2). Accordingly, under the conditions of the ongoing population outflow from rural areas and small towns to the largest urban centres (Baranovsky, 2015), these regions experience significant demographic losses, since the biggest part of migrants is expected to have final destination, namely the city of Kyiv, outside their borders. In reality, just such a phenomenon took place during the second half of the 20th century. At the same time, regional centres located further away from Kyiv (e.g. Lutsk, Rivne, Khmelnytskyi, Vinnytsia, Kropyvnytskyi, Poltava, Sumy) perform a role of gravity centres over significant shares of the areas of their oblasts. Accordingly, migrant flows in such regions are expected to be directed mainly to their regional centres. Therefore, the general demographic situation in such regions should be more favourable, since the population, despite internal redistribution from rural areas and small cities to oblast capitals, remains mainly within the boundaries of the region. Nevertheless, among the oblast centres in the western and central Ukraine, besides Kyiv, only the city of Lviv confidently spreads its influence over the entire territory of its oblast at all values of the coefficient β, and at $\beta = 1.37$ the PIA of Lviv covers also adjacent parts of the neighbouring oblasts. It is interesting that with smaller values of β, the PIA of Lviv is reducing due to the competitive influence of Kyiv, and with larger values of β it is also reducing, but this time due to competition with neighbouring oblast centres in the western part of Ukraine.

a)



$\beta = 0.92$

b)

$\beta = 1.37$

c)

$\beta = 2.50$

Figure 3. Predominant influence areas for the oblast centres and other cities with a population > 100,000

Source: own elaboration.

a)

$\beta = 0.92$

b)

$\beta = 1.37$

c)

β = 2.50

Figure 4. Predominant influence areas for the *raion* centres and other settlements with a population > 10,000

Source: Own elaboration.

In the south-eastern part of Ukraine, where a cluster of large cities is present, their PIAs constitute a complex, variegated, mosaic pattern. Here, the dominance of the largest urban centres is less noticeable, and the competition between them is more expressed. The modelling results differ significantly for different values of the coefficient β. In fact, this means that in real life, relatively small changes in socio-economic conditions and development of transport communication technologies, both influencing the actual value of β, can result in a significant transformation of the configuration of PIAs in south-eastern Ukraine. Nevertheless, large parts of the *Mykolaivska* and *Khersonska* oblasts, according to the model, gravitate towards the neighbouring oblast centres, while Dnipro, Donetsk, and Zaporizhia extend their areas of influence beyond the administrative borders of the respective oblasts.

The model suggests the real potential of some hypothetical oblast centres to be gravity centres for the surrounding areas. For instance, Kryvyi Rih could be a potential oblast centre, since its PIA covers significant total area within the *Dnipropetrovska*, *Kirovohradska*, *Khersonska* and *Mykolaivska* oblasts. It is large enough, although smaller PIAs are observed also for Melitopol, Kremenchuk and Mariupol. At the same time, the model shows that Drohobych and Izmail, which once functioned as oblast centres in 1939–1959 and 1940–1954, respectively, have very tiny PIAs because of their location in the shadow of their ‘grand neighbours’, namely Lviv and Odesa. Similarly, in the scientific literature and mass media, there were discussions about the transfer of the administrative centre of the Kyiv oblast to Bila Tserkva (Ukrainska Pravda, 2010; KyivVlada, 2020). However, even with β*=2.5*, the PIA of Bila Tserkva covers only 11.0% of the Kyiv oblast. This means that although oblast administrative bodies could move from Kyiv to Bila Tserkva, it is unlikely that the city could be the real gravity centre even for the southern part of the Kyiv oblast. In some oblasts, there are powerful sub-centres that compete with the existing regional capitals in terms of the spatial extent of the PIA (Figures 4a, 4b, 4c). In particular, in the *Zakarpatska* oblast, Mukachevo competes with the current regional capital of Uzhhorod, while in the *Volynska* oblast,

Table 2. Ratios between the area of the oblast/city of special status and the predominant influence area (PIA) of its administrative centre

City	Oblast	Area of oblast, thousand km²	β = 0.92		β = 1.37		β = 2.50	
			Area of PIA, thousand km²	Ratio	Area of PIA, thousand km²	Ratio	Area of PIA, thousand km²	Ratio
Bila Tserkva*	Kyivska	28.1	0.0	0.00	0.4	0.02	3.1	0.11
Cherkasy	Cherkaska	20.9	0.4	0.02	2.7	0.13	10.3	0.49
Chernihiv	Chernihivska	31.9	0.3	0.01	2.0	0.06	10.9	0.34
Chernivtsi	Chernivetska	8.1	2.8	0.35	10.9	1.35	13.7	1.69
Dnipro	Dnipropetrovska	31.9	21.6	0.68	22.1	0.69	15.5	0.49
Donetsk	Donetska	26.5	30.9	1.16	24.7	0.93	16.6	0.63
Ivano-Frankivsk	Ivano-Frankivska	13.9	2.7	0.19	9.5	0.68	16.2	1.16
Kharkiv	Kharkivska	31.4	56.9	1.81	49.5	1.58	36.5	1.16
Kherson	Khersonska	28.5	3.0	0.10	8.7	0.30	13.3	0.47
Khmelnytskyi	Khmelnytska	20.6	1.5	0.07	8.3	0.40	15.9	0.77
Kropyvnytskyi	Kirovohradska	24.68	0.7	0.03	4.2	0.17	12.1	0.49
Kyiv	City of Kyiv	0.8	356.9	426.86	225.6	269.88	117.3	140.33
Luhansk	Luhanska	26.7	7.4	0.28	12.1	0.45	14.6	0.55
Lutsk	Volynska	20.1	1.6	0.08	7.4	0.37	20.6	1.02
Lviv	Lvivska	21.8	25.7	1.18	40.9	1.87	29.0	1.33
Mykolaiv	Mykolaivska	24.6	6.0	0.24	10.0	0.41	13.1	0.53
Odesa	Odeska	33.3	26.6	0.80	33.9	1.02	34.4	1.03
Poltava	Poltavska	28.8	1.5	0.05	5.1	0.18	12.0	0.42
Rivne	Rivnenska	20.1	1.4	0.07	7.1	0.35	18.7	0.93
Sevastopol	City of Sevastopol	0.9	2.4	2.81	3.0	3.47	1.8	2.05
Simferopol	Autonomous Republic of Crimea	26.1	6.6	0.25	15.3	0.59	15.9	0.61
Sumy	Sumska	23.8	1.4	0.06	5.1	0.21	13.7	0.57
Ternopil	Ternopilska	13.8	1.6	0.12	7.1	0.52	10.3	0.75
Uzhhorod	Zakarpatska	12.8	0.7	0.05	2.9	0.23	6.8	0.53
Vinnytsia	Vinnytska	26.5	1.4	0.05	7.0	0.26	21.8	0.82
Zaporizhzhia	Zaporizka	27.2	17.9	0.66	26.3	0.97	17.5	0.64
Zhytomyr	Zhytomyrska	29.8	0.3	0.01	1.8	0.06	11.0	0.37

Source: Own elaboration.

Note: Although officially Kyiv is an administrative centre for both *Kyivska oblast* and the City of Kyiv, Bila Tserkva is the largest city in the *Kyivska oblast de-jure*. It has been put in the table to evaluate its potential influence as a hypothetical oblast centre.

Kovel competes with Lutsk. The question of hypothetic oblast with a centre in Uman remains debatable. On the one hand, the presence of a 'void' at the junction of five oblasts far away from powerful regional centres requires the existence of a territorial entity. On the other hand, because of relatively low population, Uman has small PIA and is thus poorly suited to be the real gravity centre for the surrounding region. Nevertheless, the relatively weak demographic and economic potential of Uman can be largely compensated by its high significance as a historical, cultural, and religious centre. Also, findings by Huff and Lutz (1995) suggest that in favourable circumstances, the city of Uman, being located in an area where the PIAs of multiple large urban centres are converging, has increased chances to grow and enter the upper tier of Ukrainian urban centres.

In some cases, interesting parallels can be drawn between the urban gravity, on the one hand, and the historical geography and regional identity, on the other. For instance, with all values of *β*, the northern part of the *Rivnenska* oblast gravitates more to Kyiv than to Rivne. This observation echoes the fact that this area shows weakened identity with a historic region of Volhynia (of which Rivne is one of principal urban centres), developing an identity with the informal region of Polesia instead (Gnatiuk & Melnychuk, 2019). Simultaneously, with *β=2.5*, Rivne spreads its influence over the former 'Great Volhynia' – the northern parts of the *Ternopilska* and *Khmelnytska* oblasts, where at least a part of local population still keeps the Volhynian identity (Melnychuk & Gnatiuk, 2018). The northern part of the *Luhanska* oblast gravitates, especially with relatively low values of *β*, towards Kharkiv. This is consistent with its affiliation to the historical region of Sloboda Ukraine, of which Kharkiv is a principal urban centre, and its current identity with Sloboda Ukraine together with a weakened identity with Donbas, although the *Luhanska* oblast is typically attributed as a part of the Donbas region (Gnatiuk & Melnychuk, 2019). The set of PIAs of Mariupol, Melitopol, and Berdiansk taken together roughly corresponds to the area of spread of the Pryazovian identity (Ruschenko, 2015).

Modelling results and second-order administrative units (*raions*)

At the regional level, the modelling results were compared with the modern network of administrative districts (*raions*), using the example of the *Volynska* oblast. As a result of the administrative reform in 2020, four *raions* were established within the *Volynska* oblast: *Lutskyi*, *Kovelskyi*, *Volodymyrskyi*, *Kamin-Kashyrskyi* (their centres are cities of Lutsk, Kovel, Volodymyr, and Kamin-Kashyrskyi, respectively).

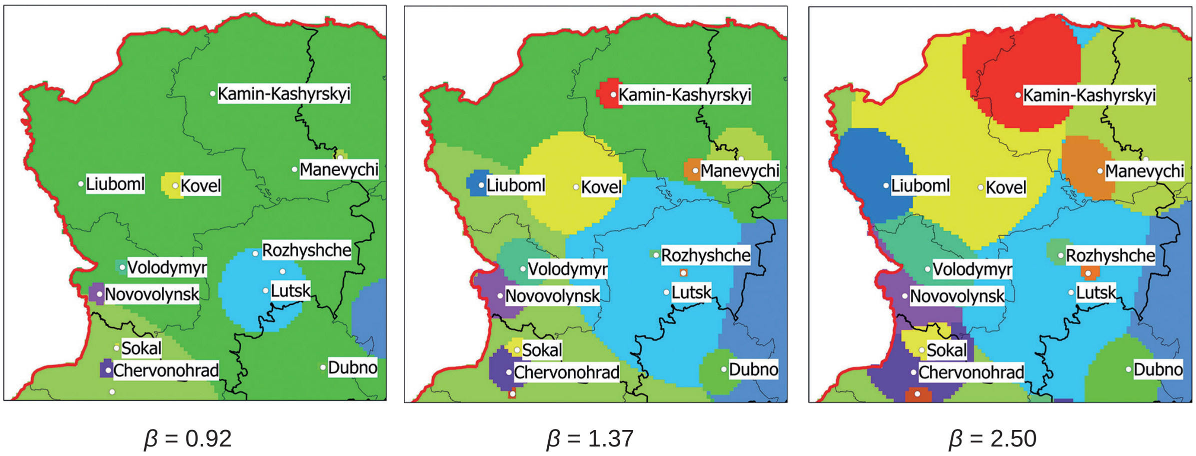


Figure 5. The Volyn oblast – predominant influence areas for the *raion* centres and other settlements with a population > 10,000.

Source: Own elaboration.

With *β=0.92*, derived from calibrating the model according to the railway passenger traffic, practically the entire territory of the Volyn oblast is covered by the PIA of Kyiv, while the small cities Kamin-Kashyrskyi, Luboml, Rozhysche, and Kivertsi, and the township Manevychi have very small PIAs, almost imperceptible in the scale of the map (Figure 5a). The predominance of Kyiv compared to Lviv in the *Volynska* oblast is supported also by the parallel observation by the authors: the majority of applicants from the *Volynska* oblast prefer universities in Kyiv rather than those in Lviv, although the latter city is located much closer. The railway network of the Volynska oblast developed and functioned in close connection with Kyiv. Its connection with Lviv first took place only in the First World War for the military purposes during the Brusilov offensive (Hrankin et al., 1996). Moreover, although railways in the *Volynska* oblast officially belong to the Lviv Railway, the main transportation is carried out in the latitudinal direction, while meridional railway connections (in direction to Lviv) are very weak. Interestingly, the ratio between the gravity of the main metropolitan centres, namely Kyiv and Lviv, works here in unison with a factor of historical geography: the *Volynska* oblast does not belong to the historical region of Galicia, of which Lviv is an informal capital, and before 1917, it was part of the Russian Empire, in which Kyiv was the de-facto capital of its Ukrainian lands.

Although at *β=1.37* (Figure 5b) all settlements with a population of more than 10,000 have their visible zones of influence, in fact, the region is divided between three cities: Kyiv, Lviv, and Lutsk. Kyiv is the strongest centre of influence in the northern part of the region. At the same time, the western and southern parts of the region falls under the influence of Lviv. The city of Novovolynsk is located there, which has close ties with Chervonohrad (in the *Lvivska* oblast), the centre of Lviv-Volyn coal basin. The important regional highway R15 (Kovel – Volodymyr – Chervonohrad – Zhovkva) passes through this territory and facilitates connections between the *Volynska* and *Lvivska* oblasts. For instance, direct bus routes Kovel–Lviv are made only by this highway R15. Another example: applicants from Novovolynsk prefer universities in Lviv more than in Lutsk. About 20% of the territory in the south and centre of the region occur in the PIA of Lutsk. The cities of Rozhyshche and Kivertsi are in the shadow of Lutsk. Because of the close economic and industrial ties, some scientists argued the existence of the Lutsk-Kivertsi-Rozhyshche industrial hub (Klimchuk et al., 1997).

Nevertheless, models with *β=0.92* та *β=1.37* are not suitable for substantiating administrative-territorial division. Model with *β=2.50* (Figure 5c) seems to be more appropriate for this task given the smaller disproportions between the PIAs and the best interpretation of the real spatial interactions in the region. According to this version of the model, the cities of Kovel and Lutsk have the largest PIAs; in addition, Lutsk noticeably extends its influence to the south-western part of the adjacent Rivne oblast. Accordingly, the allocation of the Lutsk and Kovel *raions* is well-substantiated.

Two cities are competing for the role of the sub-regional centre in the southwestern part of the Volyn oblast: Volodymyr and Novovolynsk. Although Novovolynsk has a larger population (ca. 50,400) than Volodymyr (ca. 38,100), due to its more convenient geographical location, the PIA of Volodymyr is 1.7 years larger. This substantiates the expediency of the allocation of the *Volodymyrskyi raion* with a centre in Volodymyr. However, in our opinion, it should be made larger and include the southern part of the *Kovelskyi raion*.

In the course of the administrative reform, the most controversial decision regarded the allocation of a separate *Kamin-Kashyrskyi raion* in the north-eastern part of the Volyn oblast. These are peripheral parts of the region with a low level of socio-economic development, agrarian specialisation, and large areas of forests and swamps. According to the model, Kamin-Kashyrskyi, being the only relatively big city in the area, ‘controls’ only the north-western part of its *raion*, while the southern part of the existing *Kamin-Kashyrskyi raion* gravitates to the township of Manevychi. The influence of the city of Varash (administratively belonging to the adjacent *Rivnenska* oblast) in the eastern part of the *raion* should not be exaggerated. This is the city near the nuclear power plant, which in the past performed (and currently performs) industrial functions and is weakly connected to the surrounding area. Varash is a newly created *raion* centre as a result of the administrative reform, which has just begun to serve the surrounding area as an administrative centre (before that, this function had been performed by the township of Volodymyrets). Therefore, in general, we recognise the expediency of the establishment of the *Kamin-Kashyrskyi raion*, but its boundaries should be expanded to the northwest.

Based on our model, it seems appropriate to allocate additionally the fifth *raion* with a centre in Luboml in the west-north-western part of the *Volynska* oblast. Lyuboml’s PIA in terms of area is inferior only to the PIAs of Lutsk, Kovel, Volodymyr, and Kamin-Kashyrskyi. The city of Luboml has a very convenient border transport location and great potential opportunities for international cooperation; the Shatsk National Park, and ‘Yagodyn’, the largest customs office in the *Volynska* oblast, are located nearby.

Conclusion

Practitioners, including engineers, economists, and planners have a love-hate relationship with gravity models, since they reflect well the universal features of spatial interaction, but are criticised mostly for their use as a predictive tool (Levinson & Krizek, 2008). Additionally, there is a point that the gravity model is rather inappropriate for designing a new administrative division or criticising the existing one (Kraft & Blažek, 2012). Nevertheless, the present research demonstrated that the gravity model could be a simple but effective instrument for an initial rough assessment of the urban spheres of influence (cf. Wilson & Bennet, 1985; Kraft & Blažek, 2012). Moreover, the gravity model appears to be an effective advisory tool for analysis of an existing administrative division and seeking proposals for its optimisation (cf. Śleszyński, 2015).

In particular, concerning the socio-economic regionalisation of Ukraine, the gravity model supports the six-region regionalisation schemes based on the key six metropolises as gravity centres (Shablii, 1996; Dolishnii et al., 1997) and discards the functional unity of additional socio-economic regions proposed by another family of regionalisation schemes. In this way, the gravity model highlights the current demographic and socio-economic hegemony of the few largest Ukrainian metropolises in Ukraine over the other urban centres (Pidgrushnyi & Denysenko, 2010), including over the majority of ordinary regional (oblast) centres. With regards to the first-order Ukrainian administrative units (oblasts), it was found that many oblast centres in the central and partly western part of Ukraine are not able to be gravity centres for the entire territories of their regions due to the hegemony of metropolises like Kyiv, Lviv, and Kharkiv. This indicated the lasting problem of demographic losses due to the outflow of population outside of these oblasts to the metropolitan centres, which could further exacerbate the socio-economic crisis in respective regions and the socio-economic polarisation of the country (Mezentsev et al., 2014). Similar results were achieved in Polish study for the centres of voivodeships in direct proximity to Warsaw as the largest Polish metropolis (Śleszyński, 2015). Also, we may conclude that some Ukrainian cities (e.g. Kryvyi Rih, Kremenchuk) have substantially large areas of predominant influence and thus could serve as potential new oblast centres, while the other (e.g. Drohobych, Izmail, Uman, Bila Tserkva) are gravity centres for quite tiny adjacent regions, and, therefore, are not appropriate candidates for the oblast centre status. Our conclusions about the gravity of certain regions to given urban centres are mostly supported by the data on the regional consciences and identity (e.g. Ruschenko, 2015; Melnychuk & Gnatiuk, 2018; Gnatiuk & Melnychuk, 2019), as well as by the data on historical transformations of administrative division (Gnatiuk & Melnychuk, 2020). Finally, comparing the modelling results with the configuration of the second-order administrative units (*raions*), the gravity model provides certain tips concerning the feasibility of both adding additional *raion* centres and adjusting the borders of the already existing *raions*. Of course, our assessments and recommendations are based on pre-war data, which is not relevant anymore after the outbreak of the Russian war in Ukraine, and, therefore, if applied for practical purposes, it should be amended and clarified with the use of the actual post-war data on urban and regional population in Ukraine.

At the same time, the gravity model has certain limitations and should not be treated as a panacea for regional planning and development. Both the administrative division and the regionalisation for planning purposes have a variety of functions and requirements, and thus administrative units or planning regions cannot be simply reduced to the urban spheres of influence. Moreover, planning regions should not only fix the existing situation, including the patterns of socio-spatial polarisation, but they should also play a constructive role in overcoming them (Mezentsev, 2005). Thus, modelling via gravity models will always reflect the functional ties better than the administrative or planning divisions, which is admitted by Kraft and Blažek (2012) based on the model testing on the Czech material. Unlike some similar studies, where friction of distance was determined via subjective assessment (Huff & Lutz, 1995; Kraft & Blažek, 2012; Śleszyński, 2015), our study employed the evidence-based calibration procedure, which contributes to the reliability of the modelling results. At the same time, the calibration procedure is another challenge, since it requires empirical data relevant for the simulated type of spatial interaction. The accuracy of the gravity model can be significantly increased by taking into account the real configuration of the transport network and measuring the distance via the transportation lines. Similarly, more complex or specific economic and social parameters could be used as the ‘masses’ of the cities instead of simple population; for a more advanced approach involving rather simple but complex indicator of a ‘mass’, see Śleszyński (2015). In order to better evaluate the validity of the gravity model for certain kinds of interactions, comparisons with the actual patterns of spatial interaction, e.g. commuting, could be useful (cf. Kraft & Blažek, 2012).

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