The Impact of Data Aggregation on Potential Accessibility Values

Marcin Stępniak and Piotr Rosik

Abstract The paper focuses on an investigation of the Modified Areal Unit Problem (MAUP) in a potential accessibility case study of the Mazovia region. Three different potential accessibility models were prepared based on the same theoretical background and coherent spatial data: a municipal model, a grid model and a population-weighted average travel time model. We concentrated on two main issues: the differences in the results produced by the three different models, and the impact of different methods of calculation of self-potential on these differences. The results show significant differences in accessibility values produced by the three models tested. The municipal model produced underestimated values of potential accessibility indicator in all spatial units. The differences are first of all a consequence of taking into consideration the densely populated peripheral districts of Warsaw that are 'visible' in grid-based models, but 'not visible' (i.e. averaged) in the central-location oriented municipal model. As a consequence, the total travel time between the average (population-weighted) origin-destination grid nodes is shorter than that calculated at the municipal level and the potential accessibility values are higher in both grid-based models. However, in general, the main cause of the differences of accessibility values observed is not the self-potential but rather the complexity of transportation and land use relations between neighbouring municipalities.

Keywords Potential accessibility · Modifiable areal unit problem · Self-potential · Poland

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1 Introduction

Over recent years accessibility has become one of the key questions discussed, not only in the narrow context of transport geography research, but also in a broad range of economic, social or planning studies. The possibilities that have emerged resulted from increased computational capacity and the wide application of GIS-software in accessibility studies and have provoked a growing number of studies dedicated to transport geography issues. These increased possibilities permit the use of more and more detailed geographical data prepared for wider study areas. Nevertheless, there is a significant lack of reflection on the consequences for accessibility analyses of the application of data designed at different spatial resolutions. We still have limited knowledge about how models that are based on highly disaggregated spatial data alter accessibility scale and pattern. The so-called MAUP-effect (*Modifiable Areal Unit Problem*; [1]), broadly discussed in the spatial studies literature [2–5], is still relatively undiscovered in the field of accessibility studies. The existing investigations follow the approach of Townshend and Justice [6], i.e. they concentrate on the selection of the resolution appropriate to the particular analysis focusing on the scale dimension of the MAUP [7, 8]. At the same time, they do not compare results between models that are based on administrative units and grid layers. The paper presented here tries to bridge this gap, following Fotheringham's highlighting of the need for multiscalar spatial analysis [2]. We used an assumption provided by Kwan and Weber [9], that the use of multilevel modelling to explain accessibility offers the opportunity to find geographical variations previously invisible with single level models. Finally, the aim of the paper is not only to provide evidence of the existence of the MAUP in accessibility analysis (which is quite obvious), but also, following Wong [10], to highlight locations that deserve more attention when applying the MAUP approach in potential accessibility analysis.

The MAUP is a consequence of the use of arbitrarily defined boundaries of areal units [11], i.e. the results of spatial analysis depend on the definition of the areal units applied to the analysis [3]. The impact of MAUP can be divided into two components: the scale effect and the zoning effect. The former is related to the level of aggregation of spatial data, while the latter to the redrawing or regrouping of spatial units at a given scale [1]. The difference between the units applied in the study presented (i.e. municipalities and raster-cells) is linked to the scale effect of the MAUP. The results of the accessibility study may be questioned when aggregated data is used (e.g. municipal data), while no such criticism applies to an investigation that is based on disaggregated data [3] or data that represents the continuous space [2]. Herein, the raster layer consisting of 1 km^2 grid cells is used as a proxy of disaggregated data that should be free from the MAUP effect. Due to the smoothing process [3, 10] an accessibility model that uses larger areal units (i.e. municipalities) should provide a more homogenous surface for the spatial accessibility pattern than a model that applies more detailed spatial units (i.e. raster-cells). However, in addition to the scale of spatial units, the spatial aggregation mechanism is also a key factor that determines the impact of the MAUP [10]. Therefore, our study is trying to provide information concerning the impact of the aggregation mechanisms on the results of potential accessibility analysis.

The paper is divided into five main sections. After the introduction, the potential accessibility approach is outlined. Then, in the third section, a case study area of the Mazovia region is presented, including the network and population data involved in the analysis. The same section covers the data processing procedure and three different potential accessibility models are presented in detail. In the fourth section the empirical results are presented followed by the conclusions in the final section.

2 The Potential Accessibility Approach

In transport studies, several different meanings are ascribed to the term ‘accessibility’, comprising issues relating to land use policy, infrastructure equipment, quality of transport networks, opportunities for interaction at the society level etc. The potential accessibility approach enables the observer to present one face of the multifaceted phenomenon of accessibility. Potential accessibility studies are focused on one or more of the following main themes:

- Assessment of the scale and pattern of regional accessibility disparities [12–14]
- Examination of the impact of accessibility on regional development, e.g. in terms of the location of manufacturing firms [15] or population distribution [16]
- Evaluation of new transport investments, including their impact on the improvement of overall accessibility [17−19] and/or the degree of territorial cohesion [20–23].

The proposed methodology, which is tested in the research presented here, can be applied in all of the above mentioned types of investigation. Nevertheless, due to the fact that calculations are extremely work-intensive and time-consuming, efforts should be made to provide some limits to the area of study.

Potential accessibility models are based on the distance, travel time or cost between all pairs of origin-destination nodes within the given model assuming a greater impact of larger centres than smaller ones, and a diminishing importance of more distantly located destinations [24, 25]. Its mathematical description presents as follows:

$$A_i = \sum_j g(M_j) f(c_{ij}). \qquad (1)$$

where $g(M_j)$ is the function of destination attractiveness, and $f(c_{ij})$ is a distance decay function. In the analysis presented below we use time, calculated as travel time by private car, as a distance decay element. The destination attractiveness (so-called ‘mass’) is measured as the total population attributed to a given network node (i.e. municipality or grid cell). The distance decay function responds to the negative correlation between distance and the importance of the interrelation between a given pair of nodes. Although a large body of literature exists which is dedicated to different types of distance decay functions [26, 27], we decided to restrict the tests of our methodology to only one of those most commonly used in accessibility studies: the negative exponential function ([12, 28, 29], among others):

$$f(c_{ij}) = \exp(-\beta c_{ij}) \tag{2}$$

The selection of a particular value of β parameter allows one to estimate the accessibility level in terms of different travel purposes [13]. We chose time as a distance decay element. As the methodology presented is potentially valuable for the local scale of analysis, we decided to select the β parameter of 0.023105, which corresponds to short-distance trips (e.g. commuting), i.e. median travel time is equal to 30 min [23]. The assumed median travel time is in accordance with empirical observations derived from the *Warsaw Traffic Survey* [30].

Taking this further, the incorporation of self-potential is an important factor that leads to the obtaining of proper values of the potential accessibility indicator [31, 32]. The calculation of self-potential is based on the estimation of internal travel time within a given spatial unit that is based on the radius r_i, involving the formula proposed by Rich [33]:

$$t_{ii} = \frac{0.5 * r_i}{\overline{v_{ii}}} \tag{3}$$

using a speed $\overline{v_{ii}}$ equal to 20 km/h as the assumed internal travel time. Similarly, the travel time between each pair of nodes should be increased to take account of the time needed to arrive at the origin and destination node (access and egress time). This is achieved by the application of the same formula as that used for obtaining the internal travel time (separately for both origin and destination units respectively).

3 Study Area and Data Processing

The proposed methodology has been tested on the Mazovia region, the biggest (35,600 km^2) and the most populated (5.2 m inhabitants) *voivodeship* (NUTS-2 unit) in Poland. This region is strongly monocentric, with the dominant role of the capital city, Warsaw, and its metropolitan area. However, it is also highly diverse in terms of population density and settlement structure, as well as in terms of density and the quality of road transport networks. The motorway network is unequally distributed and consists of a relatively well-developed infrastructure in the south-western part of the region, and only a few, short and fragmented motorway sections in the eastern and northern parts of Mazovia.

Apart from its internal diversity, the most significant characteristic of the study area is its central location in Poland. In spatial analysis, distortion of the results can be observed in peripheral parts of the study area [34]. The so-called ‘edge effect’ was also observed in accessibility analyses (e.g. [35, 36], among others). In order to account for this problem, potential analysis was carried out based on the study area extended to the whole country, even though the remote destinations have limited impact on potential indicator values. Thus, all municipalities in Poland are included when calculating the potential accessibility indicator, however results are only presented and analysed for those which are located within the Mazovia region (314 units).

The municipal population data for 2012 were collected from the Local Data Bank. Apart from analysis at the very detailed administrative level (LAU-2, the lowest administrative division in Poland), the model has also been developed at the higher resolution of 1 km^2 grid cells. Therefore, the population data in 1 × 1 km grid cells were prepared on the basis of the GEOSTAT 2006 population grid dataset. In order to ensure the comparability of results the GEOSTAT data were updated using 2012 population data at municipality level derived from the Local Data Bank for the estimates. Finally, due to the extremely time-consuming calculations expected, population data is only disaggregated in the case of LAU-2 units located within the Mazovia region. In consequence, municipalities located outside the Mazovia region remain unaffected.

The original, very detailed road network dataset is used in the analysis which corresponds to the road infrastructure in Poland on 1st January 2013. The database consists of approx. 70 thousand edges, divided into different road categories (motorways, express roads, dual-carriageway roads, main (national), secondary (regional) and tertiary (local) roads). Travel times are calculated based on the maximum speeds for a private car derived from the Polish Highway Code and then, adjusted downwards, taking account of impediments to driving, i.e. built-up areas, topography and population density (for details consult: [37]). The node representing a municipality is located in the centre of its main locality. The nodes representing 1-km grids are the centroids of grid cells. The latter are connected to the existing road network using a straight line to the nearest road section. Travel times between municipalities or between grid cells are received based on the shortest travel time algorithm between network nodes that represent the pair of units analysed (grid cells or municipalities).

Taking the assumed aims of the study as the point of departure, three different potential accessibility models were prepared based on the same theoretical background. Nevertheless, due to the different spatial resolution of the data involved and differences in the aggregation procedure, some slight differences can be noticed. In detail, the potential accessibility models developed and used in the research presented can be characterised as follows:

1. **Municipal model (M1)**. In the first model, every municipality is represented by one node, located in the central part of an administrative unit (e.g. main crossroads), with the mass of the unit attributed to one node. Therefore, the value of the potential accessibility indicator for municipality i (A_i) is calculated by using the travel times between node i and any other administrative node

located within the selected case study. The indicator is then calculated according to the formula

$$A_i = M_i \exp(-\beta\, t_{ii}) + \sum_j M_j \exp(-\beta\, t_{ij}) + \sum_k M_k \exp(-\beta\, t_{ik}) \tag{4}$$

where i and j are municipalities located within the Mazovia region, k is any other Polish municipality (outside the Mazovia region), and M_i, M_j and M_k are the populations of municipalities i, j and k, respectively. In consequence, $M_i \exp(-\beta t_{ii})$ is the value of the self-potential of municipality i, and $\sum_j M_j \exp(-\beta t_{ij}) + \sum_k M_k \exp(-\beta t_{ik})$ represents the sum of the potential resulting from the opportunity to access all other Polish municipalities.

2. **Grid model (M2)**. The second model is calculated similarly to the previous one however it uses grid cells in the calculation process instead of the municipalities of the Mazovia region. The indicator values received for particular grid cells are further aggregated to the municipal level using the population weighted average:

$$A_i = \frac{\sum_a ((M_a \exp(-\beta\, t_{aa}) + \sum_b (M_b \exp(-\beta\, t_{ab}) + \sum_c (M_c \exp(-\beta\, t_{ac}) + \sum_k (M_k \exp(-\beta\, t_{ak})) * M_a)}{\sum_a M_a} \tag{5}$$

where a and b are grid cells located within a municipality i, c is a grid cell located in municipality j, but outside of the municipality where a and b are located, M_a, M_b and M_c are the population of grid cells a, b and c, respectively, while k and M_k are described as above. The difference between the results received from the first and the second models is a factor of the scale dimension of the MAUP, i.e. it is a consequence of the application of different spatial resolutions.

3. **Population-weighted average travel time model (M3)**. The last accessibility model differs from the second one by the method of data aggregation from grid into municipal resolution. While the previous one aggregates the results of potential accessibility indicator values, in the third model the distance decay function includes the population-weighted average travel times between all pairs of grid-cell-nodes located in the municipalities analysed. As a result, the potential accessibility for administrative unit i is obtained using the following formula:

$$\begin{aligned} A_i = {} & M_i \exp(-\beta \frac{\sum_a \left(\frac{\sum_b (t_{ab} * M_b)}{\sum_b M_b} * M_a \right)}{\sum_a M_a}) \\ & + \sum_j M_j \exp(-\beta \frac{\sum_a \left(\frac{\sum_c (t_{ac} * M_c)}{\sum_c M_c} * M_a \right)}{\sum_a M_a}) \\ & + \sum_k M_k \exp(-\beta \frac{\sum_a \left(\frac{\sum_k (t_{ak} * M_k)}{\sum_k M_k} * M_a \right)}{\sum_a M_a}) \end{aligned} \tag{6}$$

The indirect consequence of the application of these three potential accessibility models is that they each include self-potential in a different way. The ‘municipal model’ estimates the self-potential using the radius of a circle equalling the area of the municipality in order to approximate the travel impedance, according to formula 3. In the case of the ‘grid model’, the potential of municipality i resulting from the interconnections between all grid-cell-nodes located inside i is calculated as a population-weighted average of values of potential accessibility indicator obtained for these nodes. The last model uses the population-weighted average travel times between all pairs of grid-cell-nodes located inside a municipality i to estimate the internal travel time (t_{ii}). The difference in the self-potentials of municipality i between the first and the third model is then related to the different methods of receiving the internal travel time (the area originated vs. population-weighted average travel time).

In the next section the empirical results of potential accessibility analyses are presented. We concentrate on two main issues: the differences in the results obtained from the three different models, and the impact of different methods of calculation of self-potential on these differences.

4 Results

The application of three different models produces some visible differences in potential accessibility values. In general, the grid model (M2) provides higher A_i values—the population weighted average amounts to 1,623 comparing to 1,368 in the case of the municipal model (M1), thus the A_i values are multiplied by 1.19 on average, while the difference between M1 and M3 is slightly lower (on average 1.12). Application of model M1 results leads to the largest amplitude of outliers.

Nevertheless, when standardising the results with the use of the population-weighted regional average (Fig. 1) the accessibility patterns are rather similar. In all variants the dominating position of Warsaw is clearly visible. The dominance of the Polish capital mainly results from its self-potential, although an important role of the densely populated metropolitan area, as well as the relatively good connections to the motorway and express road network in a south-westerly direction, are also

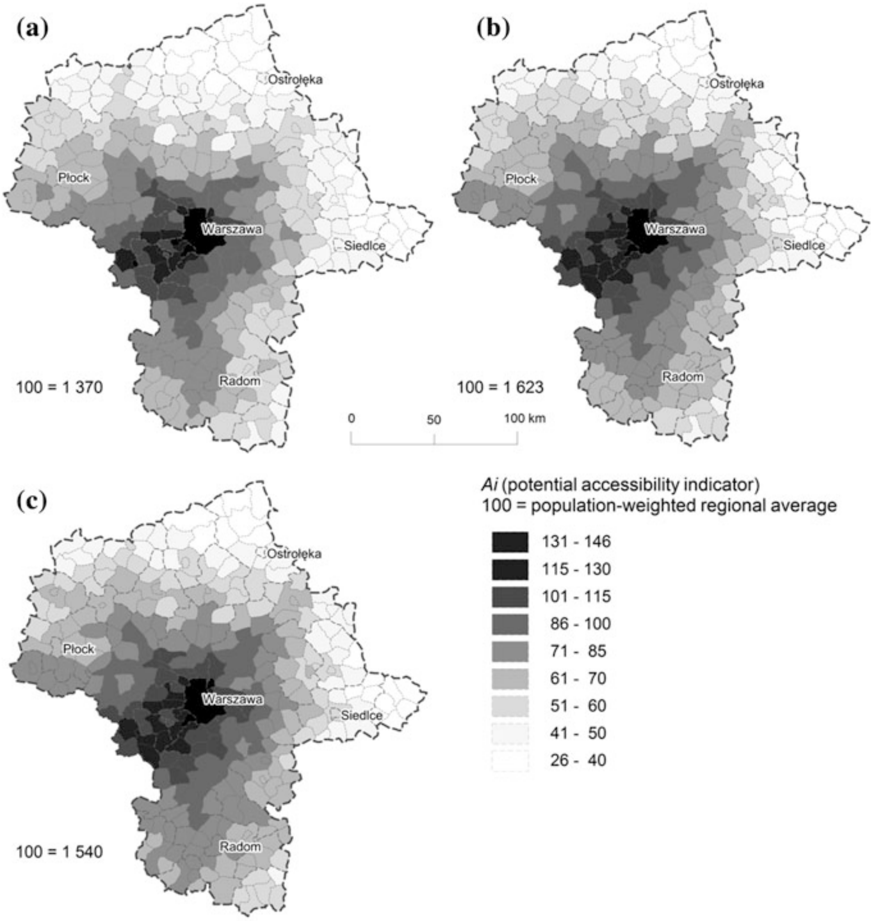

Fig. 1 Potential accessibility values (Ai) in the Mazovia region. **a** Municipal model (M1), **b** grid model (M2), **c** population-weighted average travel time model (M3)

significant factors. Furthermore, the regional disparities in the Mazovia region are mostly influenced by the existence of two connected poles of relatively higher accessibility visible at the national level (cf. [23]) which are located in the central part of Poland, including Warsaw and Łódź metropolitan areas, and the southern part of the country containing Cracow and the Upper Silesia conurbation. The intraregional accessibility disparities are even strengthened by the location of the majority of the high quality infrastructure in the most accessible part of the region linking Warsaw with Łódź and the central part of Poland. As a result, better road accessibility is observed in the south-western part of the Mazovia region, while peripheral areas in the eastern and northern part of the region are clearly less accessible. Nevertheless, there are some exceptions to the above rule resulting from the location of a short section of express road in the north-eastern environs of Warsaw and a motorway bypass of Minsk Mazowiecki 50 km to the east of Warsaw (Fig. 1).

Comparisons of potential accessibility values resulting from the individual models are presented in Fig. 2. The differences reach a maximum of almost 50 % and mostly affect the environs of Warsaw, which is a direct consequence of the "sprawl" of mass from the city centre (in the M1 model) towards peripheral, residential districts with high population densities (Fig. 2a). As a result, the distance to the highly populated districts of Warsaw from suburban municipalities is smaller and the accessibility values in the M2 model are higher. Moreover, there is a clear positive correlation between increasing distance from Warsaw and diminishing differences in *Ai* values. The differences are also more visible where accessibility

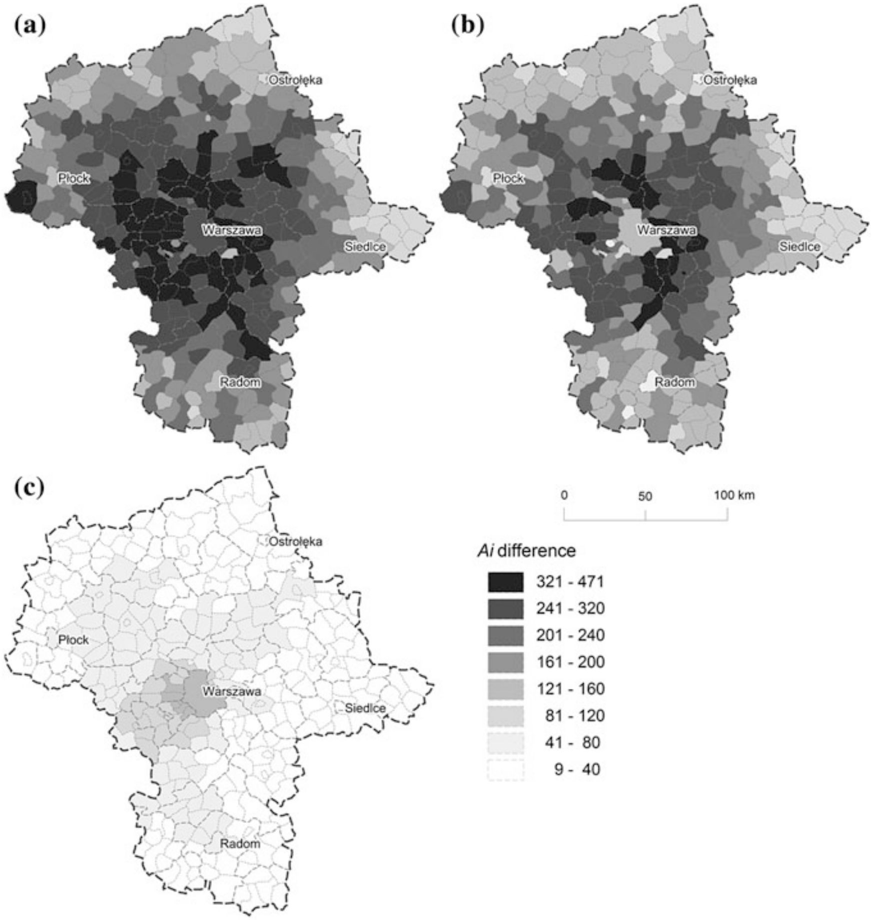

Fig. 2 Differences in potential accessibility values. **a** Ai(M2) − Ai(M1), **b** Ai(M3) − Ai(M1), **c** Ai (M2) − Ai(M3)

values are higher. Consequently, the smallest differences are noticed in the extreme north and east of the Mazovia region. Furthermore, the grid model gives higher accessibility results for municipalities located along rivers and with a high density of forest. This may to some extent be explained by the concentration of population along main roads and the low population density in the peripheral areas.

The differences between models M3 and M1 present quite a similar pattern (Fig. 2b), although the scale of dissimilarities is lower than between models M2 and M1. The grid model (M2) generates higher values than the population-weighted average travel time model (M3) especially in the case of Warsaw and those areas which are located along the transport corridors (Fig. 2c).

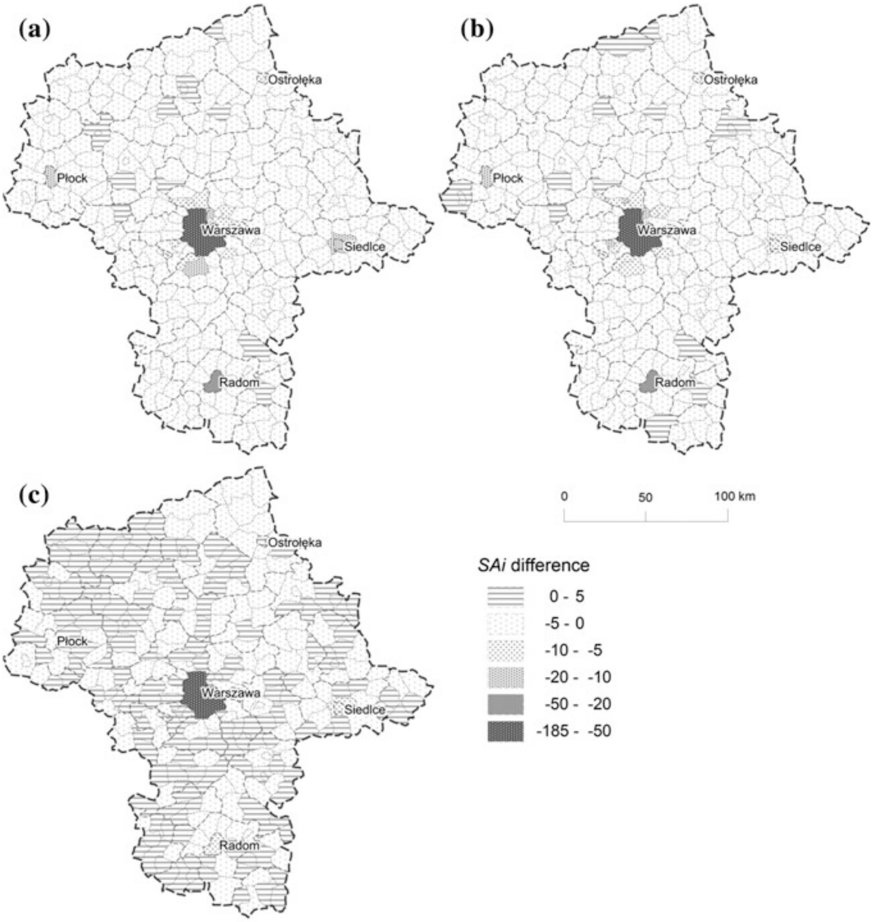

Fig. 3 Differences in self-potential values (SAi). **a** SAi(M2) − SAi(M1), **b** SAi(M3) − SAi(M1), **c** SAi(M2) − SAi(M3)

One of the possible explanations of the differences described above is that they are the consequence of different methods of calculation of self-potential. To test this hypothesis, a comparison of self-potential values calculated within particular models was prepared (Fig. 3). Even a first glance at the maps enables one to disprove the hypothesis. The differences between the values obtained from the models being compared are totally the inverse of that expected with this explanation. In general the self-potential values obtained within the municipal model (M1) are higher than in other models while the potential accessibility values are lower (cf. Figs. 2 and 3). In the case of Warsaw and most other big cities (so-called 'subregional centres') the self-potential values obtained from the municipal model are much higher than those in both grid-based models (and especially those in model M2). In consequence, the method of calculation of travel time between municipalities or data aggregation method should be treated as the main source of the differences of A_i values, rather than the method of calculation of self-potential.

5 Conclusions

The potential accessibility analysis for the Mazovia region shows both significant differences in the accessibility values obtained from the three models tested and a relatively stable spatial pattern when the results are standardised according to the population-weighted average. The latter suggests that the potential accessibility indicator is, to some extent, independent of the aggregation mechanism applied for the investigation. This applies in the case of comparison of differences of accessibility values over space. Nevertheless, the differences are clearly visible when investigating the overall level of potential accessibility. The municipal model (M1) provides comparatively low values of potential accessibility indicator for all spatial units, while the application of the population-weighted average travel time model (M3) and particularly the grid model (M2) result in significantly higher values.

The results are in line with the assumptions made on the basis of the concept of a smoothing process. The application of larger units (municipalities in the model M1), provokes more smoothing than other models, thus the values should be lower. The application of the M3 model causes significantly less smoothing in comparison to the M1 model, but more in comparison to the M2 model, thus the results are in-between the others, closer to the latter than to the former one. Nevertheless, the most important seems to be the fact that the higher number of relatively short-distance trips provides the higher A_i results, even though the mass ascribed to destination nodes is substantially lower. This explains the difference between models M1 and M2. The difference between models M1 and M3 is the consequence of the different method of calculation of travel time between each pair of units. The results show that the (population-weighted) average travel time (M3) is significantly lower than the travel time derived directly from the O-D matrix between nodes that represent municipalities (M1). Thus, the A_i values in the M3 model are significantly higher than in the M1 model.

The differences between models are a consequence of taking the densely populated peripheral districts of Warsaw into consideration, which do not influence the grid-based models (M2 and M3), but do have an impact on the central-location oriented municipal model (M1). Furthermore, the population is more concentrated in the municipalities which are located along the main transport networks or those where urbanised land constitutes a relatively low percentage of the area (e.g. woodlands, river valleys). In consequence the total travel time between the average (population-weighted) origin-destination grid nodes is shorter than calculated at the municipal level. For that reason the potential accessibility values are higher in both grid-based models.

Second, in case of almost all administrative units, the self-potentials produced by the municipal model are higher than in both of the grid-based models. This effect can either be caused by excessive internal speed impedance or by too short internal distances. However, the internal speed of 20 km/h at the municipal level seems, in general, to even be too low when compared with other accessibility studies that include self-potential values [8]. This speed is also lower than that observed in the Warsaw metropolitan area [30]. Therefore, we conclude that the internal distance used to calculate the self-potential should be increased beyond the length of 0.5 radius proposed by Rich [33] (for detailed discussion concerning the approximation of travel impedance please consult: Frost and Spence [38]).

Third, the differences in accessibility values between municipal and grid-based models are not caused by the distinct method of calculating the self-potential values. Therefore, our hypothesis is that the main cause of the differences of A_i values observed is the complexity of transportation and land use relations between neighbouring municipalities. Nevertheless, the issue of the impact of disaggregation of population data (or even more generally: the mass applied for the potential accessibility model) should be further investigated. Although our analysis provides some empirical results presenting the consequences of the use of different types of spatial data (i.e. administrative units vs. raster cells), the role of the MAUP in accessibility studies is still an open question.

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