Daily Spatial Footprint of Warsaw Metropolitan Area (Poland) Commuters in Light of Volunteered Geographic Information and Common Factors of Urban Sprawl. A Pilot Study

Veranika Kaleyeva[1] and Piotr A. Werner[2(✉)]

[1] Institute of Urban and Regional Development, Targowa 45, 03-782 Warsaw, Poland
v.kaleyeva@gmail.com
[2] Faculty of Geography and Regional Studies, University of Warsaw, Krak. Przedm. 30, 00-927 Warsaw, Poland
peter@uw.edu.pl

Abstract. Urban sprawl directly affects on length of commuting. Acquisition of commuting data is based on theoretical (deductive) approaches, limited individual small observation samples or indirect phenomena like e.g. remote sensing night light data images. Volunteered Geographic Information (VGI) make possible deeper insight into the daily spatial footprint of commuting and is related to urban sprawl. Data acquired during the collection of VGI data reveal some new aspects of spatial phenomena, which can be additionally analyzed. VGI data concerning spatial phenomena involve both geotagging as well time stamps of acquisition, which in turn make possible indirectly inferring about spatial and temporal move of people. Analysis of the available spatial and temporal VGI data in context of national surveying acquired resources (INSPIRE) and confronted to modelling approach of commuting is the subject of pilot study of Warsaw functional urban area. The results are promising due to inter alia, generalization of huge volume real data observations set unlike to formerly used theoretical modelling.

Keywords: Volunteered Geographic Information (VGI) · Urban sprawl · Commuting patterns · Spatial behavior

1 Introduction

Urban sprawl (suburban sprawl) is defined as "the rapid expansion of the geographic extent of cities and towns, often characterized by low-density residential housing, single-use zoning, and increased reliance on the private automobile for transportation." [1]. Urban sprawl is perceived as an inherently dynamic spatial phenomenon [2] and is the subject of huge number of research papers and books and recognized and studied in numerous regions of the world due to growing interest since the introduction of the term in 1937 [3] in processes of suburbanization due to observed general tendencies of

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urban growth (and decline) during (at least) last century. Primarily, it is the outcome of people individual decisions where to live and work, which in turn have implication on different social, economic and environmental spatial phenomena processes. The first, direct implication of urban sprawl is spatial and temporal configuration of commuting to the centers of cities. The main presented problem in this pilot study touches the problem of relation of urban sprawl, understood as a state of spatial extent of metropolitan area, and its relation to commuting, assuming that urban sprawl directly affects on length of commuting. Reconstruction of spatial and temporal daily commuting within the boundaries of functional urban area was studied for the case of Warsaw Metropolitan Area from 2008 until 2018. This new insight was possible using Volunteered Geographic Information (VGI) data sets in context of official collected and shared statistical and geospatial data collected by surveying services (thereafter in paper termed as INSPIRE in international context). Assumption hypothesized that VGI make possible deeper insight into the spatial and temporal pattern of commuting and reconstruction of daily spatial footprint of commuting, which in turn is related to actual state of urban sprawl. The main question under study was where and, at what time the prevailing number of people: inhabitants and/or visitors were during the day (24 h) within the boundaries of metropolitan zone. However, analyzed data are only the sample, the subset of the whole phenomenon, although certainly pinpoints statistically the fragment of commuting in Warsaw Metropolitan Area.

Short synopsis of the thereafter threads of study involve state-of-art discussion concerning common factors of urban sprawl as well as advantages and weakness of use of different VGI data, characteristics and spatial extent of study area, more detailed discussion of methods used and rational of application. Next, there are presentation of the results of pilot study, discussion and conclusions. The proposed approach is the first step of supplementary studies related to former studies concerning spatial interactions and urban sprawl processes in the context of land use change.

Use of VGI data is nowadays the expanding way of the scientific approaches due to dissemination of ICT smartphones applications using geospatial technologies. However, they are usually strictly defined and related to geoportals and/or spatial databases aimed usually precisely defined scope of data like e.g. monitoring some elements of natural environment, people movements (e.g., GPS sport applications) as well as monitoring traffic of cars, airplanes, trains, ships. These data involve also a lot of additional information concerning also date and time of acquisition and technical features of ICT personal devices (e.g. tags, saved metadata of photos) and sometimes the metadata features of the elements of ICT nearby (e.g. in case of used in this study OpenCellId spatial database). This pilot study is trying to use this additional data.

Finally, the aim of the study has been defined as the reconstruction of commuters' daily footprint. However, there is hidden assumption in the research investigation, that the greatest part acquired database is just the result of commuters recorded observations, but it is also possible that the results were recorded by other visitors or inhabitants taking also part in the traffic.

2 Common Factors of Urban Sprawl and Impacts on Daily Behavior of Inhabitants and/or Visitors

"A variety of definitions for sprawl have been put forth that describe sprawl as a specific form of urban development with low-density, dispersed, auto-dependent and environmentally and socially-impacting characteristics" [1]. The term can be used to describe both a state of landscape as well as process. The evaluation of the existing definitions for urban sprawl reveals that most of them involve three spatial aspects: the expansion of urban area, the increase of dispersion of build-up area and low-density development in suburbia with a high land take per person [2]. The shift in population and employment density from city core to suburbia has been identified as a main characteristic associated with spatial expansion of urban area [4]. Distribution of settlement area and communing are interdependent in a complex way. Residents make choices between settlement areas taking into consideration the cost of housing and commuting between homes and work places, consequently in areas where incomes are high and travel costs are low the sprawl is more common [5]. Availability of roads, private car ownership, low cost of fuel and poor public transport in city core drive urban sprawl. In contrast, development of rail transportation raises residential density around access points [6]. At the same time, urban sprawl influences mobility patterns.

The consequences of urban sprawl include a variety of responses concerning, inter alia, landscape quality, loss of arable soil, recreation areas, shrinking open spaces, functional and spatial separation of places for living and working, and (last but not least) large numbers of commuters [2].

Commuting, making up a large part of all journeys worldwide and many resource-demanding transport investment, is important for the overall economy and for the everyday life of many people. It is related to spatial division of labor and relay on spatial structure: housing market, technical and social infrastructure and employment conditions. Commuting is perceived generally as substitute of migration and is joint or sequential decision where to live and/or to work [3]. The phenomenon is related to labor mobility and is also the consequence of different factors affecting the labor market conditions, especially for the countries characterize 4th stage of demographic transition.

However, some recent studies recognized the problem of commuting time, which will subside as these sprawled housing boom areas age and try to re-conceptualize "low density, auto-dependent urban form as a normal part of the urban growth process" [7]. The huge number of researcher approaches focused on analysis of urban form and function aimed monitoring and modelling of urban dynamics developing urban growth models [8]. Urban growth models relay on changes of land use maps including (not rarely) sparse time-intervals and subjective interpretation in documentation of urban growth [9]. The new approach postulate use of spatial metrics for quantifying key morphological characteristics of the urban fabric from profile- and patch-based metrics, originating from the field of landscape ecology, and introducing also building-based metrics aimed machine-learning-based land use and urban form classification [8]. Appreciating these geodata, they are obtained usually from officially collected and

shared state – or enterprise, commercial resources. However, this concerns infrastructure, not the people and their spatial behavior, which can be only inferred about.

Another possibility is to use common, volunteered socially collected data, aimed, inter alia, easing every day life in metropolitan areas or solving defined, ad hoc, social as well scientific problems. These crowdsourcing geodata sets, VGI expose, sometimes, unexpected values added despite of obvious assumed targets.

3 Advantages and Weakness of Use of Different VGI Data

"The convergence of newly interactive Web-based technologies with growing practices of user-generated content disseminated on the Internet is generating a remarkable new form of geographic information. Citizens are using handheld devices to collect geographic information and contribute it to crowd-sourced data sets, using Web-based mapping interfaces to mark and annotate geographic features, or adding geographic location to photographs, text, and other media shared online. These phenomena, which generate what we refer to collectively as volunteered geographic information (VGI), represent a paradigmatic shift in how geographic information is created and shared and by whom, as well as its content and characteristics" [10].

VGI may suffer from different quality. Given the tremendous flow of VGI, the problem of information quality is of increasing importance. The reasons for this could be: data is generated by heterogeneous actors using different technologies and tools that have different levels of detail and precision, serve heterogeneous purposes, and have no systemically defined quality control measures [11]. It is crucial to realize that people do have perception bias. They perceive and consequently define imprecisely geographical regions and spatial relations. Moreover "people typically think and communicate about the world in terms of vague concepts" [12 p. 185]. Volunteers involved in collecting data lack a coherent conceptualization of their activities; mostly they do not follow "sharp semantic boundaries". Thus, differences in the quality of the data they collect are also determined by limited knowledge of the space being studied [13]. At the same time, it worth to emphasize that the most VGI sites require very little expertise in order to participate, except for Internet and mobile phone literacy [14]. It worth to mention also that volunteers sometimes more frequently reach to faraway locations and collect various data about them, than officially registered or surveyed information or by use and interpretation of remote sensing acquired data.

Lack of knowledge refers also to the traditional geographic information (GI) quality criteria. International Organization for Standardization (Technical Committee, ISO/TC 2117) developed a set of international standards that define such a quality (standard 19138, as part of the metadata standard 19115): completeness, consistency, positional accuracy, temporal accuracy, and thematic accuracy.

On the other hand, there is no objective measures of the accuracy. Some authors [15] point out although users of Google's search do not have any benchmarks to which they could compare the results they obtain, yet people continue to rely on google. In such a case people tend to make their assessment based on own judgment whether google results fit their search purpose at a given time. Considering this, if a substantial group of people find some VGI fit for their purpose, then VGI becomes of higher

quality compared to other information sources (at least for a given purpose in a well-defined context). The volunteers providing VGI may be treated as "markers for the quality of their contributions". If the volunteers are perceived as trustworthy, then VGI becomes perceived as trustworthy too. Researchers suggest that integration of the spatial and temporal dimensions of trust may generate a new form of reputation which they call "event-reputation of volunteers using distance and time" [15]. It means that volunteers that are close to an event (spatial dimension) at the time of the event occurrence (temporal dimension) are given an event-reputation for a given time concerning reporting about this particular event. Such a reputation of VGI may not only be constituted for a time being of event, but can also be extended further through continuous reporting from those concrete volunteers through the whole course of the event, and in this way to result in establishing kind of permanent reputation for these volunteers about a certain local area, and the data they collect. In this way, a progression of trust in VGI can be anticipated over time. One must admit that VGI have unique propagation channels of informational trust, which can be treated as a feature that distinguishes VGI from other data sources.

New elements were added to the discussion of geospatial data quality in the 21st century through the development of Web 2.0 and the availability of Global Positioning System (GPS). The interactivity of the new web technology helped create a large amount of user-generated content (UGC). Scientists [16] analyze the specific example of cutting-edge VGI usage and compares it to traditional way of data gathering project by national surveying offices (INSPIRE). There is no doubt that the combination of geospatial information extracted from the two aforementioned different initiatives is truly beneficial to several stakeholders: public authorities, professionals, businesses, researchers, and NGOs. VGI based project has its advantages and disadvantages. It has full license interoperability and is founded on modern technologies. However, by its very flexible nature it suffers from the lack of rigorous data specifications, since contributors are free to use tags different from those agreed by the community. It seems the challenges of that particular VGI project play a part in broader VGI data classification problems such as:

- data is likely prone to subjective classification,
- remote contributions and flexible contribution mechanisms in most projects,
- uncertainty of spatial data and non-strict definitions of geographic features.

Guiding implementation of VGI projects using data collection protocols could help in reducing its potential drawbacks [16].

In many aspects VGI may be considered a significant innovation [17] in view of social, economic and scientific as well as educational aspects, notwithstanding the fact that it generates additional data, additional information, which is not usually recorded by the statistical and/or surveying services. Particularly noteworthy is its cultural dimension. VGI is a phenomenon of user-generated content that has fairly recently led to the adoption of open access and a collaborative approach and sharing of information resources. Nevertheless, the user-generated data are often viewed as a by-product, however it is hard not to appreciate its up-to-date dynamic and collective environment in which diverse information, opinions, experiences, and skills can be aggregated to offer extensive brand new data sources. Today it is difficult to imagine - in the era of

growing internet and technology - not to see the potential that lies in the use and development of VGI, which, along with its increasing legitimization and verification - may even begin to incline the official registrars to complement official (traditional) databases with these new information.

4 Data Resources and Methodology of Pilot Study

Sources of data used in pilot study involve both official INSPIRE data sets shared publicly as well as VGI data. The spatial extent of data cover the sheet as minimum bounding rectangle of boundaries of functional urban area of Warsaw metropolis, i.e. between the coordinates (in decimal degrees): +19.8 and +22.5 longitude and +51.6 and +53.1 latitude.

To reveal the location of people: inhabitants and/or visitors – the subset of OpenCellID database has been used. Source of presented data is subset of database acquired from opencellid.org [18] (accessed Feb. 2019), which counted over 40 million records identifying base transceiver stations (BTS) and, inter alia, timestamp of the acquisition. In fact, BTS information is derived from voluntary crowdsourcing reports and later verified. OpenCellID is actively updated crowdsourcing database collecting GPS location data for cell identifiers. It had already been previously used in scientific research and its advantages and disadvantages are recognized [19, 20]. However, the volume of stored data since 2008 lets assume, that is close to real current situation at the global scale.

Records of data involve geolocation and (UNIX Epoch) timestamp. This information, due to fact, that UNIX time is not a true representation of Coordinated Universal Time (UTC), made possible to define the local time of reported acquisition. It means that the approximate local time (as well the day, month and year) and geolocation of smartphone user reporting his/her position is possible to define using this timestamp. The procedure is similar to `mapscaping` the geotagged tweets.

Additionally the maps of spatial extent of built-up areas [21], as well as, roads and railways maps have been used from Polish INSPIRE data resources [22]. These maps were used clipped to the aforementioned spatial extent.

4.1 Spatial Extent: Warsaw Metropolitan Area (Poland)

Warsaw (Polish: Warszawa - is the capital and largest city of Poland. The metropolis stands on the Vistula River in east-central Poland and its population is officially estimated at 1.791 million residents within a greater metropolitan area of 3.33 million residents, which makes Warsaw the seventh most-populous capital city in the European Union. The city limits cover 517.24 sq.km, while the metropolitan area (MA) covers 6,100.43 sq.km. Warsaw is an alpha global city, a major international tourist destination, and a significant cultural, political and economic hub. Its historical Old Town was designated a UNESCO World Heritage Site. Statistically Warsaw has the largest number of connections with neighboring cities in Poland (905) [23, 24]. Location of study area covering both Warsaw MA and city limits is presented in Fig. 1.

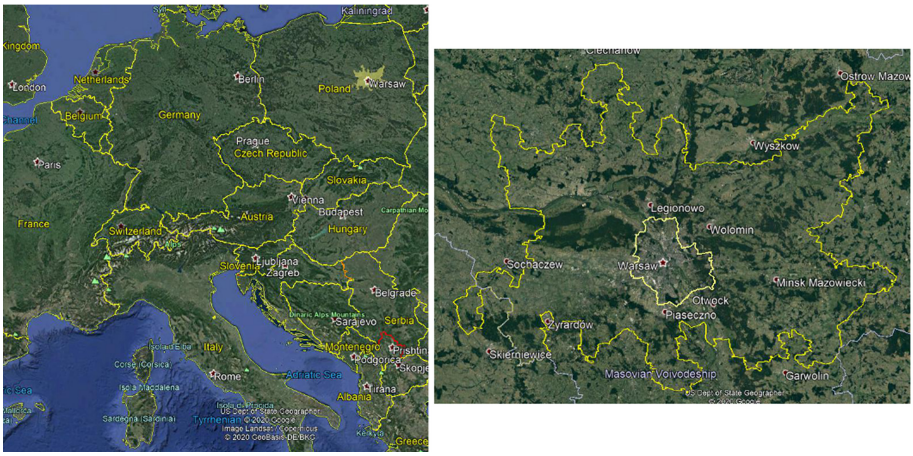

Fig. 1. Warsaw Metropolitan Area 2020; left: in Europe; right: WMA and city administrative boundaries.

The Warsaw MA is the core part of the rural-urban region of Masovian voivodship in Poland and can itself be considered as a rural-urban region of smaller scale [25]. The spatial distribution of acquired BTS data is presented on top of built-up areas layer of WMA (including height of buildings in meters, Fig. 2) according to acquired geodata subsets: OpenCellId [18] and GHSL Data Package [21]. The aim was visual comparison of spatial distribution of the observations with spatial location of possible origins and destination of moving people.

The recent, actual spatial extent of research pilot study is defined according to Eurostat Geoportal [26]; The subset of dataset contains urban clusters, based on local population data. Urban clusters are defined as groups of contiguous raster cells of 1 sq. km size, having a population density of at least 300 inhabitants/sq. km and a total population of at least 5000. The definition of urban clusters underpins the urban/rural typology of NUTS3 regions and the degree of urbanization classification of local administrative (LAU2) units. The boundaries of WMA are delimited based on Polish INSPIRE resources [22].

4.2 Warsaw MA Urban Sprawl and Projections

The movement of people, especially commuting, was indirectly taken into account, and treated as the factors of two (recently) observed main urban processes: urban sprawl and land uses change. Former studies of spatial land uses change simulations often included suitability and zoning layers created based on different evaluation of spatial accessibility (roads), maps of different types of land use (at the starting point of time) treated as prohibited zones or planned zones of change, as well as population distribution.

After 1989 suburbanization, and the transformation of peri-urban areas in the region of Warsaw MA have been characterized by spatially varying intensity, with high

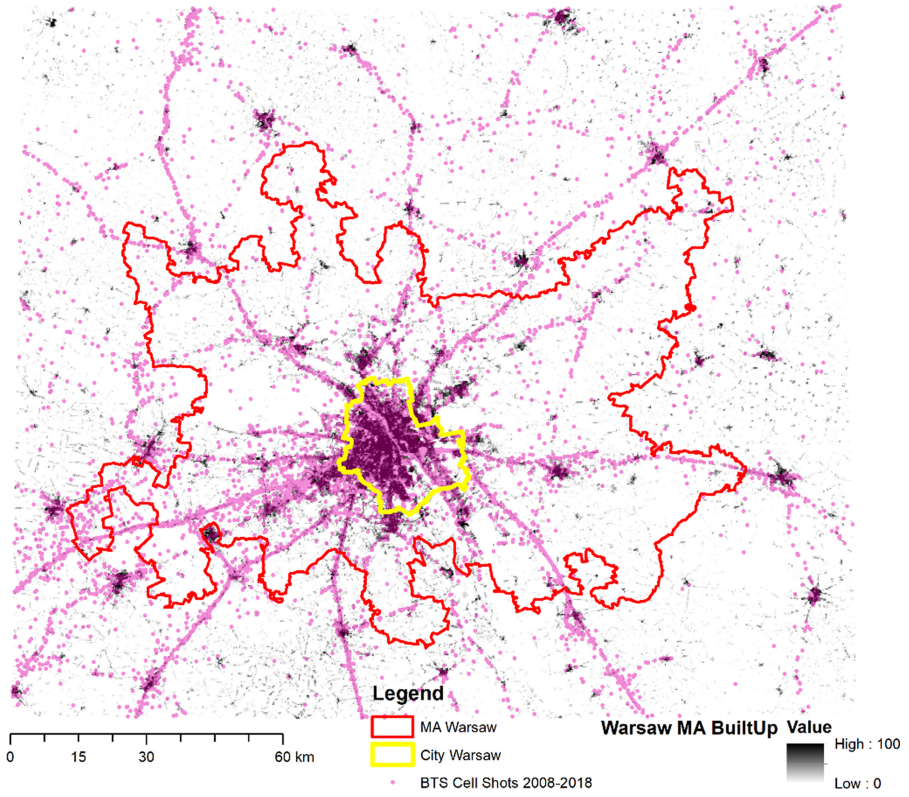

Fig. 2. Spatial distribution of acquired subset of BTS data presented on top of built-up areas layer of Warsaw Metropolitan Area WMA (including height of buildings in meters [21]).

overall dynamics accompanied by lack of spatial order, i.e. by typical urban sprawl phenomena. The previous existing zone of second homes from the 1970s has been partly invaded by new residential, as well as some commercial and industrial functions, connected with the globalized economy, while the prime recreational activities have moved further out into the region's rural hinterland. Simulation of different scenarios, generated using the application of Metronamica ML (multiple layer) framework, reveal noticeable distribution of both residential, as well as industrial and commercial land uses [25] (Fig. 3).

Prospective use of acquired real observations of population movement in space, with the set of continuously recorded data during time, create the possibility to verify the results of past models of urban sprawl and urban land use change simulations. However, for the moment, it is only the strategic aim. The hereafter-described procedure is only the proposed method, looking for the appropriate way to include VGI data into the set of future tools to be possibly developed.

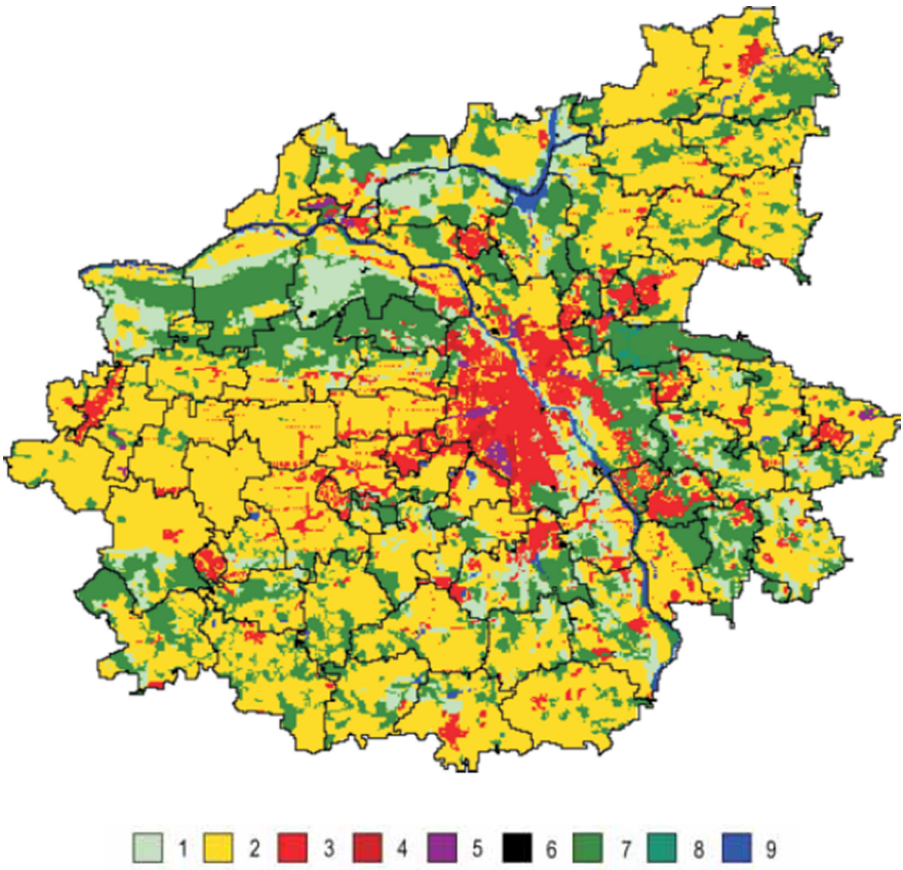

Fig. 3. Simulated land use in Warsaw MA 2025. (Limits to growth scenario Metronamica ML) [25]. Boundaries of WMA: 2012; legend of map: (1) green urban areas, (2) agricultural areas, (3) urban fabric, (4) industrial or commercial units, (5) transport areas, (6) mineral extraction or dump or construction sites, (7) standing forests, (8) natural and semi-natural vegetation, (9) water courses and bodies. (Color figure online)

4.3 VGI Insight and Methodology

Up to now the prevailing inferring concerning urban sprawl are based on registered statistical geodata and population (INSPIRE). However, it is possible to depict the spatial and temporal aspects of commuting people, using aforementioned VGI geodata.

The approach use Data Metrics method to map statistical parameters of a data set under study. Data Metrics method is used to gain information about data points in the form a grid, however it does not interpolate the data to obtain a Z Order Statistics. The data is divided into search sections where the calculation will be performed. The Z Order Statistics provide specific statistical information about the data that is specified within the search radius. The Z grid node values will have the same units as the original data file. These data values can be significant to calculate if the goal is to demonstrate areas of

statistical interest. The data that is found in the search radius will be sorted from least to greatest and then the following statistics can be calculated [27]. For the pilot study, the Z median statistics has been analyzed and mapped. The median absolute deviation value is calculated by determining the median in the search range and then deviations are taken for each value. Once the deviation values are determined, then the median is taken from that set and assigned as the Z value for that grid node. The statistics for data locations are concerned with the location of the data points. All procedures have been completed using Golden Software Surfer and ESRI ArcGIS software.

The main aim was to reveal the time of the day (hour, not minutes) when the report of certain BTS has been acquired. This meant that the VGI – reporting person was in this moment in given location.

5 Results of Pilot Study

One of the purposes of social and economic geography is indirect understanding by analyzing spatial patterns and inferring spatial and temporal processes [28].

Approach using Data Metrics Z Order Statistics reveal typical picture for commuting phenomena, i.e. concentric rings around the boundaries of capital city – WMA (Fig. 4). There are zones more active early in the morning and contrary – destinations located further down – active in the evening, when people starting or finishing their daily duties. There are also 'black holes' – where the people are active before sunrise or long after sunset – located far from the city.

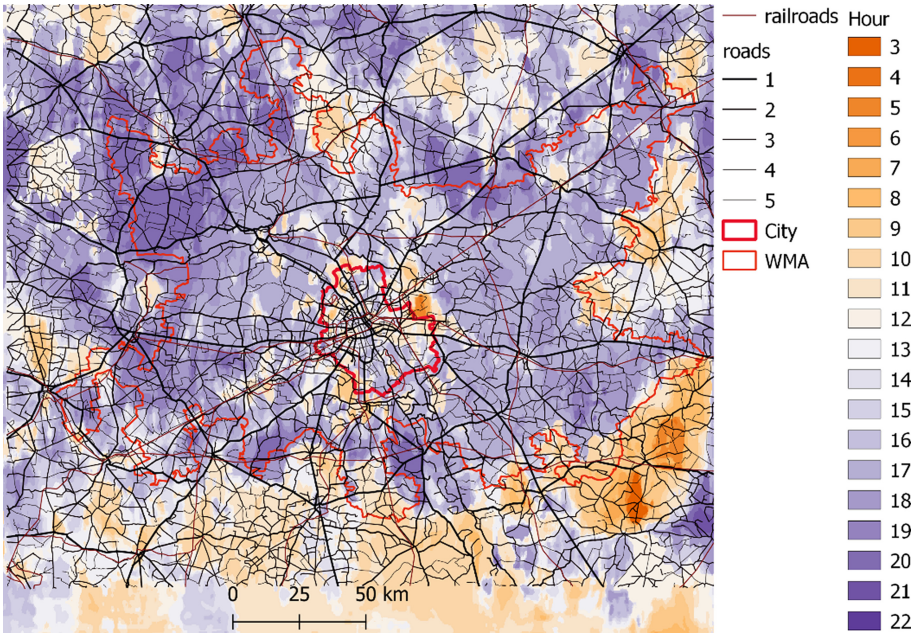

Fig. 4. Daily spatial footprint of inhabitants/visitors/commuters of Warsaw Metropolitan Area. Data Metrics Z Order Statistics (Median). Integer values represent hours of the day (24 h).

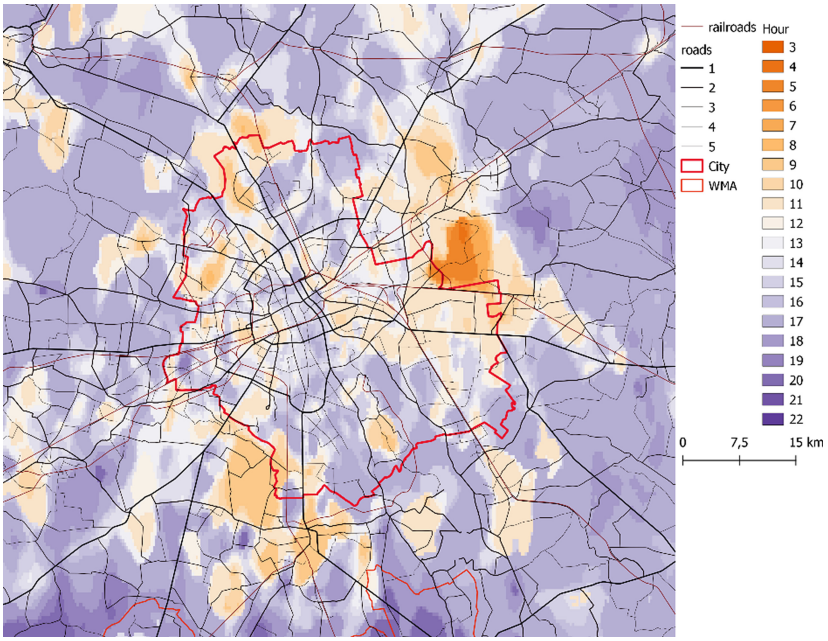

Fig. 5. Daily spatial footprint of inhabitants/visitors/commuters of Warsaw City. Data Metrics Z Order Statistics (Median). Integer values represent hours of the day (24 h).

Interesting phenomena reveal inset, containing zoom of Warsaw city itself (Fig. 5). The main activity of people in center of Warsaw City (business district) falls at noon and afternoon hours. The map shows, of course, the median hours of main (suspected) activity. Also reveals some areas, which are inside the administrative zone of the city characteristics of residential areas – active in the morning and late evening. Zooming the map shows when and where these activities are more intensive inside the administrative region of city itself.

The possible next steps for this study would be zoning procedure, evaluating of different regions of spatial and temporal intensity of VGI observations and comparison to observed qualitative and quantitative changes of land use, as well as estimation of urban sprawl. This is a far-reaching objective, and this examination is only the first step of a possible future procedures.

6 Conclusions

Some depicted observations and mapping human activity based on reports of timestamps of generalized subset of OpenCellId reports confirm spatial and temporal regularity, which shows well-known facts concerning the commuting. In fact, these VGI geodata may be possible tool to confirm some spatial and temporal models of urban activity. Especially taking into account some specific time intervals, e.g. weekends or differences for typical seasons (winter and/or summer). These time ranges seems

interesting in context of planned development of the rail and road networks as well as prospective locations of residential areas. The reported results are only the pilot study aimed to verify the usefulness of VGI data.

Later it has been found out fact just after completing this pilot study that there are different versions of OpenCellId database available in the internet for several past subsequent years. For the moment in this pilot study, the studied data aimed to present daily spatial footprint (idealistically) are in fact rather an average spatial footprint for every hour of day during a period of 10 years. This discovery makes possible not only spatial but also the temporal comparisons, evaluating the dynamics of these footprints not only for urban sprawl or land use changes.

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