ISSN 2079-9705, Regional Research of Russia, 2022, Vol. 12, No. 2, pp. 227–240. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2022.

Quantifying Spatial Structure of the Largest Regional Centers in Russia: General Patterns and Typological Features

E. O. Saveleva*

Department of Architecture and Urban Studies, Perm National Research Polytechnic University, Perm, 614990 Russia
**e-mail: e.saveleva@pstu.ru*

Received August 8, 2021; revised January 21, 2022; accepted April 28, 2022

Abstract—The quantitative analysis of urban form has long become an important component of both academic research and practice contributing to a better understanding of how cities function and evolve. Despite the abundance of studies quantifying urban structures of the cities in developed countries, the reach of modern quantitative methods into studying the urban form of the Russian cities has been limited. This paper aims to fill in the knowledge gap of the quantified urban form characteristics of the largest regional centers in Russia presenting a GIS-based multivariate analysis of the similarities and differences between their urban structures. The results of the spatial modelling form the base for the development of the typology of urban structures produced via the *k*-means statistical clustering technique. Attributing the city to one of the three types of urban form identified—compact, discrete, or extended—allows obtaining a better understanding of the city's spatial organisation that should in turn feed into the grounded strategy for its development.

Keywords: urban structure, Russian cities, quantitative analysis, *k*-means clustering, typology

DOI: 10.1134/S2079970522020216

INTRODUCTION

Within the domain of urban geography and planning, urban morphology, as the study of cities' spatial structures and their underlying formation processes, has long become an important component of both academic research and practice. The study of urban form contributes to our understanding of how cities function, and urban policies are often informed by planners' perceptions of the prevailing spatial structure of cities. Different spatial structures perform differently and may react to urban policies and interventions in a special way. Given this, urban planners need to be aware of the potentials and inefficiencies inherent to the city's current urban structure.

Although the history of urban form research may be traced back to the start of modern planning and urban studies (Burgess, 1935; Harris and Ullman, 1945; Hoyt, 1939), the topic has recently regained increased attention. With the overall shift towards "sustainable development" as a guiding concept, the search for ideal, or sustainable, urban form has gained new momentum (Breheny, 1992; Burton et al., 2003). This manifested itself in the growing popularity of the "compact city" movement and the growing number of studies measuring the degree of urban compactness or, conversely, the degree of the city's sprawl (Angel et al., 2011).

The appearance of geographic information system (GIS) technology with various software packages that have become available for analysing spatial development patterns has brought a new breath of air in this field of research and has allowed expressing the features of urban form, including compactness, quantitatively (Clifton et al., 2008). One of the first studies providing the means to the systematic analysis of urban compactness via the modern tools was the one by Torrens and Alberti (2000), who offered metrics for measuring multiple aspects of sprawl, which was not, however, supported by verification on any empirical prototypes. The early research in this area was confined to the developed countries, specifically to the USA (Epstein et al., 2002; Ewing et al., 2002a; Galster et al., 2001). The pioneering study by Galster et al. (2001) has identified eight dimensions of sprawl—density, continuity, concentration, clustering, centrality, nuclearity, mixed uses and proximity—and tested them in 13 US cities via GIS modelling. The following decades saw a growing number of academic publications on the variety of urban form measurements in the European context (Kasanko et al., 2006; Patacchini et al., 2009). These studies, inter alia, have highlighted both the differences in the development patterns between Europe and North America and variations in urban sprawl across different cities within Europe. The ongoing attempts to quantify the sprawl were also made in developing countries such as China (Jiang et al., 2007) or India (Sudhira et al., 2004). Some of the studies have even taken a global perspective on urban form and its quantitative characteristics (Huang et al., 2007; Schneider and Woodcock, 2008).

Hence, the studies in the field have continuously contributed to the understanding of the different dimensions of spatial structure in various urban settings. Some of them have also tried to link the quantified characteristics of sprawl or compactness statistically to the manifestations of their impact on urban mobility (Ewing and Cervero, 2001) or social equity (Burton, 2000). Thus, the studies of this kind have not only formed a separate direction of research but also have given rise to many related topics dealing with the economic, social, and environmental implications of the thrive towards compactness (or either natural tendency towards sprawl), the potential effects it has on ecosystem, social vitality, and urban mobility (Haaland and van den Bosch, 2015; Jenks and Jones, 2009).

Despite an abundance of studies on the quantitative expression of urban form made in different contexts, in Russia and other post-socialist states, such research is still in a preliminary stage with only a few studies approaching this topic. Kovacs (2019) presents a rigorous review of the literature on measuring post-socialist urban form, pointing to the fact that European cities with socialist past still have specific urban structures, which strikingly differ from West European cities. Setting aside the somewhat limited number of quantitative studies of post-socialist urban form, their findings might be only partially useful for understanding the spatial structure of the non-European cities of the former Soviet Union. Due to the longest history of "socialist experiment" Russia (along with the few other post-Soviet states) became the main ground for the implementation of the Soviet urban-planning model, and development patterns, including the process of urban expansion, in Russian cities were different from that of other post-socialist countries (Kostinskiy, 2001).

The current study aims to expand understanding of the post-Soviet urban form moving from mostly qualitative discussion to quantitative analysis. The aim is addressed via assessing the urban structure of the largest regional centers in Russia with a range of spatial indicators. It also provides a valuable addition to understanding the Russian cities' spatial organization by developing an up-to-date typology of the regional centers' urban structures based on the combination of characteristics. In the light of the extreme limitations that experiment as a method has in the field of geography and urban planning, any type of comparative analysis and classification by one of the features are highly useful tools for generalization and insight into city's place among others (Lappo, 1997). It is all the more useful to have a typology, which is based on a combination of several features at once, as this allows giving a comprehensive description of cities feeding into the grounded strategy for their development.

QUANTITATIVE ANALYSIS OF URBAN FORM: A LITERATURE REVIEW

Existing studies on quantified urban form cover a wide range of aspects and consider the topic from multiple angles, either performing temporal analysis that makes a record of change in development patterns and structural characteristics (Deng et al., 2009; Herold et al., 2003) or comparing urban form between different cities (Huang et al., 2007; Schneider and Woodcock, 2008) or even combining both approaches (Angel et al., 2011).

Schwarz (2010) distinguishes two major directions of discussion with respect to measuring urban form. The first approach stems from the field of landscape ecology and is based on investigating maps of urban footprints or land cover derived from satellite images, wherein the change in the built-up (or urbanized) area is generally used as the main parameter for quantifying urban sprawl. Such studies either directly use satellite remote sensing data or derive information from various databases built on satellite data for delineating the boundaries of the built-up areas, sometimes referred to as Morphological Urban Area (MUAs) (Wolff et al., 2018). Schneider and Woodcock (2008), for instance, evaluated urban sprawl for 25 mid-sized cities worldwide using the Landsat dataset, while Inostroza et al. (2013) employed the Landsat imagery to develop a spatial database for 10 Latin American cities to quantify their spatial patterns. Corine Land Cover (CLC), produced by the European Environment Agency (EEA) on the basis of satellite photos, is a common tool for exploring the urban form of the European cities, sometimes in combination with demographic data (Guérois and Pumain, 2008; Kovács et al., 2019; Schmidt et al., 2015; Schwarz, 2010). Another open tool for urban form research—the Global Human Settlement Layer (GHSL), coordinated by the European Commission Joint Research Center—combines population data from census information and built-up area data from satellite images. Recent studies employing the GHSL data include Guastella et al. (2019), tracking spatial expansion in 27 European cities, and Mahtta et al. (2019) applying cluster analysis to determine five urban growth typologies across 478 million-plus cities. Studies of this kind focus on the amount of urbanised area, which is undoubtedly an important component of urban structure but does not give an understanding of the internal spatial arrangement within the cities.

The studies falling in the second strand according to Schwarz (2010) add a socioeconomic perspective to the urban form research and make use of various population-related indicators (Ewing et al., 2002b; Frenkel and Ashkenazi, 2008; Kasanko et al., 2006; Schneider and Woodcock, 2008; Tsai, 2005). Tsai (2005), for example, used four quantitative variables to differentiate compactness from sprawl in the US metropolitan areas: size (population-wise), density, the degree of equal distribution, and the degree of clustering. The urban economists' perspective on a city's spatial organisation implies the wide use of such concept as the population density gradient, which is based on the assumption that population density decreases at a constant rate in the direction from the city center towards the periphery (Clark, 1951; McDonald, 1989). The term is believed to be introduced into wide circulation by urban geographer Colin Clark, who studied twenty cities to prove that the density distribution generally presents a negatively sloped exponential curve (Clark, 1951). The large literature that followed Clark's work presented the empirical results that are supportive of negative population density gradients, with exceptions in socialist cities and cities under apartheid (Bertaud and Malpezzi, 2003; Bertaud and Renaud, 1994).

Compared with the rich literature on quantified urban form in various cities worldwide, relatively little research on this topic has been carried out in Russia. Arguably the most developed direction of research employing quantitative techniques of assessing spatial structure in Russia is the delineation of urban agglomerations. A recent study of this kind is the one by Antonov and Makhrova (2019), delineating urban agglomerations on the national scale based on a two-hour isochrony transport accessibility to the city center. While the traditional approaches in this area make use of the population census data, there are now also alternative sources of information like the local mobile operators' data, which, for instance, allowed defining the boundaries of the Moscow agglomeration based on determined stable commuting flows (Makhrova and Babkin, 2020). Focusing primarily on the functional linkages between the center and the periphery in the agglomerations, these regional studies leave the peculiarities of the internal spatial structure of the cities beyond the scope. The landscape ecology direction of urban form analysis has not gained much development in Russia yet, but separate case-specific studies mapping urban land cover changes using remote sensing data nevertheless appear (Choudhary et al., 2017; Dokhov and Sinitsyn, 2020). The metropolitan level studies that employ some elements of quantitative analysis of the internal spatial patterns tend to focus on a single city, most often Moscow (Kirillov and Makhrova, 2019), while those attempting to introduce comparative perspective rely mostly on qualitative assessment or may contain some methodological limitations such as using administrative area (rather than the actual built-up area of the city) in the denominator when calculating population densities (Ptichnikova, 2020).

Thus, the review showed that studies by researchers trained in various disciplines have made, especially recently, considerable progress measuring urban form. It also demonstrated that the authors attempting to assess the urban form in a quantitative manner have employed very different approaches and applied multiple metrics. The selection of indicators for quantification of the spatial structure generally depends on the scope of the study, peculiarities of the urban form in the study region, and data availability. Many authors have called for standardisation in operational definitions and measurement protocols (Clifton et al., 2008), some have tried to bring some order and uniformity in the variety of spatial metrics (Fleischmann et al., 2021; Frenkel and Ashkenazi, 2008; Jaeger et al., 2010). Still, there is no unified practice of selecting indicators for analytical use that is commonly accepted and applied, and the set of measures varies from study to study. The approach towards the investigation of urban form in Russian cities constitutes a special challenge, considering the scarcity of data and previous measurements to build on. Thus, the aim is to quantify the urban structures in a simple way that allows comparisons and further development of the topic but at the same time is optimally suited for identifying all the specificities of the post-Soviet urban form founded in Russian cities.

METHODOLOGY

Sample of Cities

Upon the case selection for comparative studies, it is important that considered cities are commensurate, that is belonging to the same size category. Russian urbanization is now passing the stage of the outstripping development of major cities when it is the largest cities that show the highest rates of development. Major cities are facing an especially daunting challenge in search of the optimal spatial organisation: due to the larger average settlement radius, the need for an effective urban form is more pronounced there. The choice of the largest regional centers as a subject for research is also justified by the availability of statistical and other data. The status of the million-plus cities combined with the status of regional administrative capitals makes "the largest cities" group more researchable among other Russian cities. The study bypasses the two largest Russian cities—Moscow and St. Petersburg, which stand out among others both in size and in terms of their urban structure. The exclusion of these two cities allowed for a homogeneous sample suitable for comparative purposes. Thus, the evidence base for this quantitative analysis comes from the 13 centers of Russian regions with a population of over 1 million people, namely (in decreasing order of their population as per 2020 Federal State Statistics Service (Rosstat) data): Novosibirsk, Yekaterinburg, Nizhny Novgorod, Kazan, Chelyabinsk, Omsk, Samara, Rostov-on-Don, Ufa, Krasnoyarsk, Perm, Voronezh, Volgograd.

The methodology of data collection for the spatial analysis of the urban form has been through open-source software. The urban form characteristics of the cities in the study were calculated with the help of

Geographical Information Systems (GIS) using OpenStreetMap data, satellite imagery and land-use maps. The estimation of the population density distribution across the largest Russian cities' territories has been carried out through processing of the 2016 LandScan dataset, which is a high-resolution global Population Data Set copyrighted by UT-Battelle, LLC, operator of Oak Ridge National Laboratory. This population distribution model represents an ambient population (average over 24 h) distribution at approximately 1 km spatial resolution. The result of the GIS-based spatial analysis of the Russian cities' urban structure comes in the form of the quantitative dataset of various urban form characteristics: built-up area, density, shape index, population dispersal index, network indirectness index and sprawl index.

Definition of Spatial Metrics

In the presence of a high variety of measurable urban form characteristics, the intention of this study was to select the ones that would most accurately and clearly present the specificities of the post-Soviet urban structure found in the sample cities taking into account the availability of the necessary geographical and statistical data. The considered metrics allow quantifying all the basic characteristics of the urban structure such as density (the ratio between the number of residents and the area), configuration (refers to the geometry of the urban built-up area) and accessibility (quantified by measuring the street length from the residents of a city to its center) (Frenkel and Ashkenazi, 2008). All the calculation formulas were adapted from the graphic-analytical method by M. Yakshin, which allows to evaluate compactness of the city's spatial structure and correlate it with other cities based on the specially developed index, termed as *sprawl index* in the current study (Sosnovskiy and Rusakova, 2006; Yakshin et al., 1979). The graphical-analytical method used in the study involves linking the observed development parameters and population data to kilometre zones with a step of 1 km measured along the roads from the city center (each city center was determined individually and tied to the intersection of major transport routes and the concentration of retail trade and services).

The *built-up areas* of the cities have been determined using OpenStreetMap cartography, satellite imagery and land-use maps. In this exercise, any water bodies, rural, recreational and any other kind of undevelopable land were excluded from the final figure. The urbanized area is also used as a denominator in the calculation of the general *densities*, which gives a more valid result.[1]

[1] Generally, city's average density is calculated simply as the ratio of the total population of the city to its total land area. Yet these figures appear to be practically meaningless seeing the unknown amount of rural and any other kind of undevelopable land included in the city limits.

The shape of the city's physical imprint is expressed via the *shape index,* which is an important characteristic of urban form having a significant influence on the overall compactness. Since the most compact of all possible forms is a circle, the shape index is calculated as the ratio between the average distance of the built-up area to the city center (meaning between the city center and each grid cell of the built-up area) and the average distance to the center of a circle with the area equal to the built-up area.

$$S_i = \frac{\sum iS_i l_i / S}{0.377\sqrt{S}},$$

where l_i is the aerial beeline distance of the *i*th grid cell from the city center, weighted by the area of the grid cell S_i, S is the total built-up area of the city (adapted from Sosnovskiy and Rusakova, 2006).

The *dispersal index* is calculated as the ratio between the median distance to the city center per person and the average distance of the built-up area to the city center. This index is akin to one proposed by Bertaud and Malpezzi (2003), whose dispersion index can be calculated as the product of the *shape index* and the *dispersal index*.

$$D_i = \frac{\sum i n_i l_i / N}{\sum i S_i l_i / S},$$

where l_i is the aerial beeline distance of the *i*th grid cell from the city center, weighted by the share of the population in this grid cell n_i, N is the total population of the city, S_i is the area of the grid cell, S is the total built-up area of the city (adapted from Sosnovskiy and Rusakova, 2006).

The efficiency of the network configuration (allowing to avoid unnecessary distance travelled) is assessed via the *network indirectness index.* This indicator is determined based on the graphical plotting of kilometre-gram—a set of lines, all points of which are equally distant from the city center, where distances are measured along the streets.

The *network indirectness index* is calculated by the following formula:

$$NI_j = \frac{\sum j n_j d_j}{\sum i n_i l_i},$$

where d_j is the distance measured along the roads of the kilometre zone *j* from the city center, weighted by the share of the population in this zone n_j, and l_i is the aerial beeline distance of the *i*th grid cell from the city center, weighted by the share of the population in this grid cell $n_{i.}$ (adapted from Sosnovskiy and Rusakova, 2006).

The *sprawl index* is an aggregate measure of city compactness equal to the product of the following three quantities: the shape index, the population dispersal index, and the network indirectness index.

Table 1. Summary of the urban form characteristics of Russia's largest regional centers

No.	City	Founded, year	Population, million people	Built-up area, km^2	Density, people/km^2	Shape index	Dispersal index	Network indirectness index	Sprawl index
1	Novosibirsk	1893	1.603	273.75	5855	1.41	0.70	1.25	1.25
2	Yekaterinburg	1723	1.456	296.94	4902	1.37	0.65	1.26	1.12
3	Nizhny Novgorod	1221	1.262	221.03	5708	1.34	0.91	1.19	1.45
4	Kazan	1005	1.232	240.19	5129	1.40	0.74	1.28	1.33
5	Chelyabinsk	1736	1.199	276.59	4334	1.23	0.68	1.49	1.25
6	Omsk	1716	1.178	316.70	3721	1.37	0.67	1.25	1.15
7	Samara	1586	1.170	188.47	6206	1.61	0.67	1.33	1.43
8	Rostov-on-Don	1749	1.125	171.66	6555	1.21	0.74	1.27	1.14
9	Ufa	1574	1.116	234.88	4749	1.97	0.65	1.23	1.58
10	Krasnoyarsk	1628	1.083	209.34	5173	1.39	0.72	1.33	1.33
11	Perm	1723	1.048	255.21	4106	1.69	0.71	1.26	1.53
12	Voronezh	1586	1.040	215.87	4817	1.32	0.62	1.28	1.06
13	Volgograd	1589	1.016	270.73	3751	2.17	0.88	1.25	2.39
	Average				5001	1.50	0.72	1.28	1.39

Compiled by the author.

Multivariate Typology

The application of quantitative methods to the urban form of the largest regional centers produces a multivariate dataset on each of the sample cities. The results of quantifying the urban structures feed into the analysis of the similarities and differences between them and form the base for the development of their typology. Statistical clustering becomes a useful method by analysing all the calculated variables simultaneously. The division of the sample cities into classes is performed with the help of the *k*-means method (performed in the R statistical package), which is one of the most commonly used unsupervised machine learning algorithms for clustering. The method requires the number of groups *k* to be pre-specified by the analyst. It then classifies all the observations in the defined number of groups so that the total intra-cluster variation (or total within-cluster sum of squares) is minimized i.e., the observations within the same cluster are as similar (or as close to each other) as possible, whereas observations from different clusters are as dissimilar as possible.

RESULTS AND DISCUSSION

General Patterns

The result of the GIS-based spatial analysis of the Russian cities' urban structure has come in the form of the quantitative dataset of various urban form characteristics summarized in Table 1, including built-up area, density, shape index, population dispersal index, network indirectness index and sprawl index.

After completing the spatial modelling phase, it is important to visualize the individual urban form attributes, as this is a first step in becoming familiar with the morphological characteristics of the sample regional centers. Figure 1 offers a representation of the largest Russian cities' spatial structure (ambient population density distribution) in 3D form, which allows visualization of geospatial data showing the overall shape of residential areas and concentration trends. Upon the scrutiny of the GIS models of the sample cities' spatial structures, it appears that all the cities have common features that manifest themselves to varying degrees, but nevertheless are shared by all the 13 regional centers. The general type of the sample city's spatial structure is a sprawling one, with relatively dispersed population and sudden peaks of population concentration at the periphery.

The built-up area values measured in the GIS models enable comparative analysis as well as further calculations of quantitative urban form characteristics. The position of the Russian regional centers relative to other cities in the international sample in terms of the ratio between population and the built-up area is shown in Fig. 2, where two city types lie at the opposite ends of the population density spectrum: low-density North American cities and high-density Asian ones. Sample cities along with the European cities take an intermediate position.

While the general density as the most widely used indicator of sprawl does not unequivocally classify Russian cities as sprawling, in the case of the post-Soviet cities it is crucially important to consider also how this density is distributed across the city. For comparison purposes, the dispersion index, which

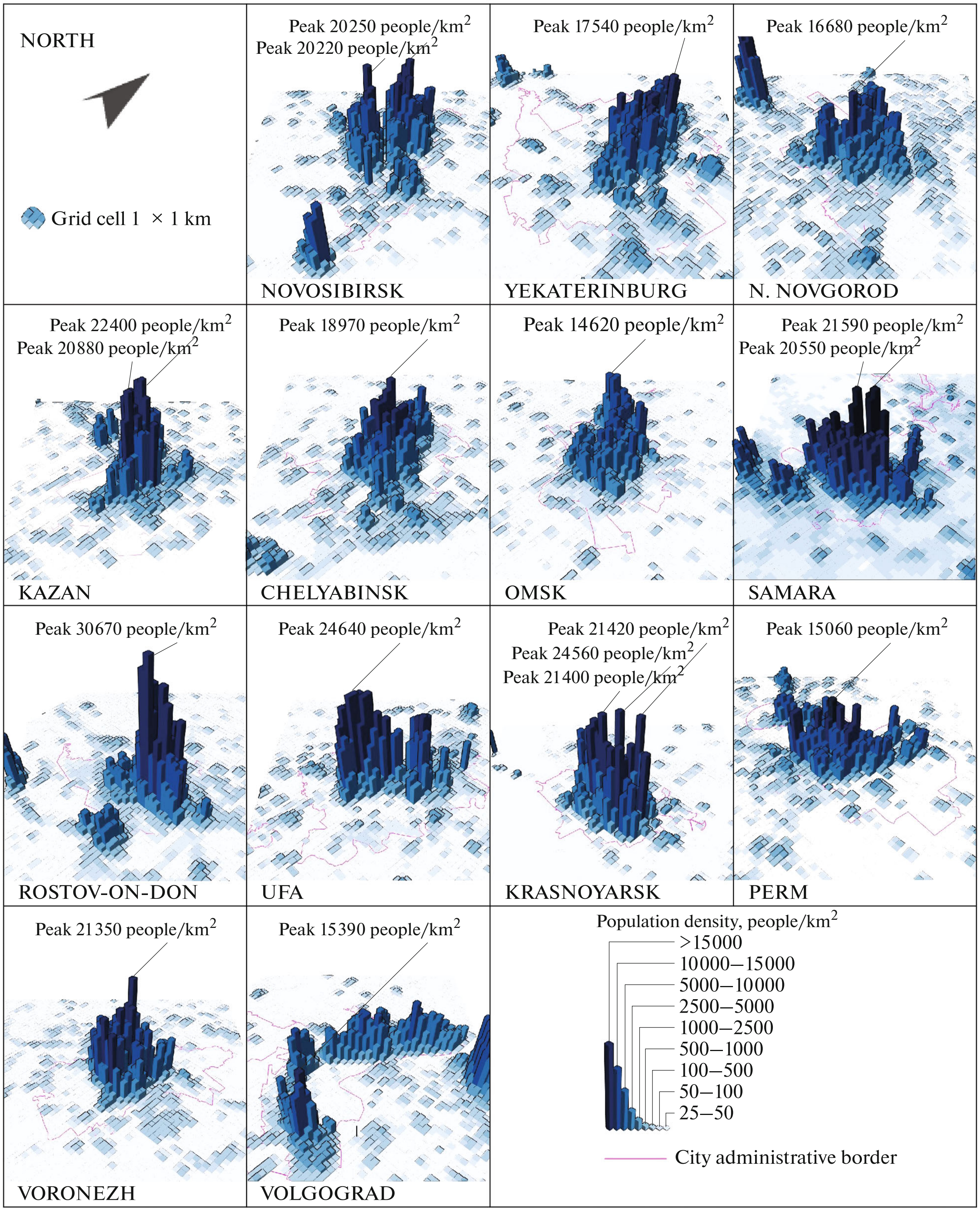

Fig. 1. Population density distribution in the largest regional centers of Russia (scale 1 : 1250000).

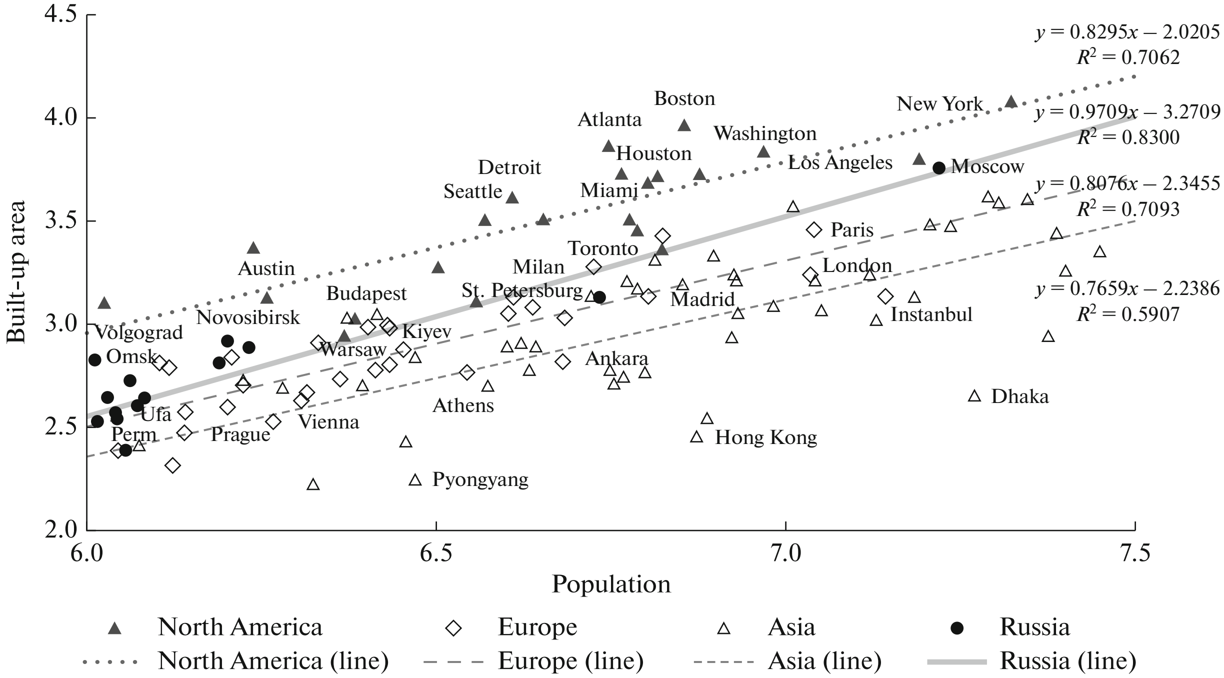

Fig. 2. Built-up area–population relation for the world cities (logarithmic scale).

shows the effectiveness of the established distribution of population across the territory of the city (Bertaud and Malpezzi, 2003), was calculated; the results are shown in Fig. 3. Most sample cities have a dispersion index equal to or greater than 1, which indicates a reduced concentration of population around the city center. For the city and its residents, it means lengthy transport communications and increased commute times (as well as relatively low efficiency together with the high cost of public transport), which in turn leads to the increased use of personal transport and correspondingly high negative environmental impacts. From the economic perspective, smaller values of the index indicating the city's compactness are more favourable, since a city with a smaller distance between places of residence, work and consumption is more functional for labour and consumption markets. Yet the international comparison shows that the lower values of the dispersion index are mostly characteristic of Asian cities densely built within the confined urban space, while the Russian cities' indicators are generally close to 1 as in most European cities or, in some cases, much higher. One reason for this inefficiency of the sample cities' urban structure is that most of their urbanisation occurred under the influence of the Soviet practice of urban development. In all the sample cities, the sharp growth, both population and territory-wise, occurred in the 1920–1930s with the construction of the new plants and factories that occupied the vacant plots often located at a considerable distance from the existing urbanised areas. This was accompanied by the development of completely new settlements with housing for job-seeking migrants (usually low-quality temporary dwellings), which later became the city's peripheral neighbourhoods. The mass housing construction from the 1960s onwards became the solution to the prolonged housing crisis but also resulted in significant territorial growth and thus increased population dispersion.

Another simple and widely used method of assessing the spatial distribution of the population is the analysis of the city's density profile. Whereas the most common type of the density profile of a capitalist city includes a "density crater" in the center with a peak density immediately after it and the gradual decrease towards the periphery (Bertaud and Malpezzi, 2003), the density profile of the sample cities have abnormal peaks of density outside of the city core, which are visible in Fig. 1. These findings are consistent with the earlier study by Koncheva and Zalesskiy (2016), who have plotted not population, but housing density profiles for the same cities determining density peaks at various distances from the city center in all of them except for Omsk. In three of the cities—Samara, Volgograd and Ufa, these peaks have almost reached the residential housing density marked in the central parts. The overview of the density peaks' location in the sample cities is presented in Table 2. The analysis of the housing density profiles revealed two ambivalent trends in post-Soviet residential development: post-1992, residential density growth was registered both in the central areas and at the peripheral greenfield areas in all cities studied. The tendency of essential increase in housing density within the central areas

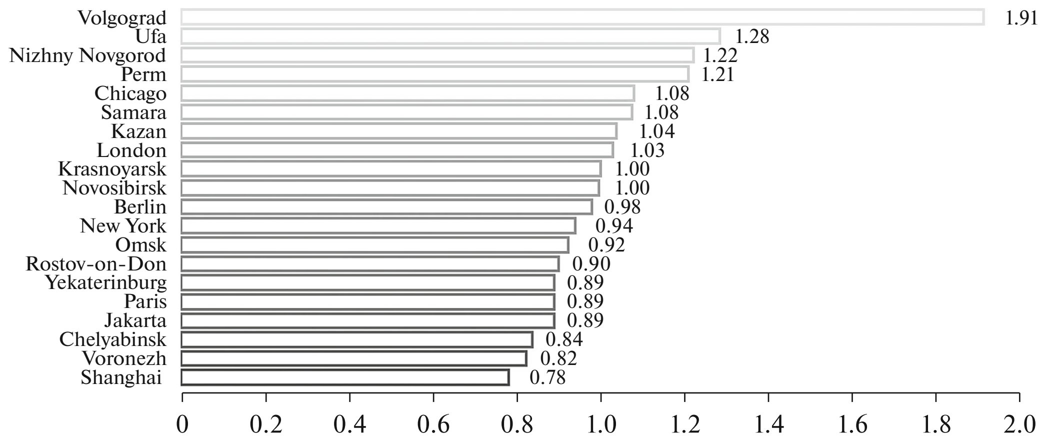

Fig. 3. Comparative dispersion indices of Russia's largest regional centers and selected cities around the world.

was prevalent in the early post-Soviet years, whereas the outward expansion came into full force during the housing construction boom induced by the high oil prices in the 2000s.

Thus, Russian cities have not undergone the process of suburbanisation in typical for capitalist cities form of single-family detached housing,[2] as the peripheral development was instead dominated by the high-density residential neighbourhoods. The territorial expansion characteristic of Russian cities in the post-Soviet period is a very special type of sprawl, completely different from the American one, and, most interestingly, is not close to the one proliferated in the post-socialist countries of Eastern Europe. The studies of land-cover changes in the cities of Estonia, Latvia, Slovakia, Poland, Bulgaria, and others show that they have also witnessed rapid expansion (Kovács et al., 2019; Schmidt et al., 2015) but, unlike Russian cities, once-compact Eastern European cities acquired sprawling peripheries comprising low-density (single-family) housing and commercial development (shopping, offices and warehouses). An unprecedented scale of the decentralization processes became a universal phenomenon for all the post-socialist cities in Europe in line with the global tendency. Yet, in Russia, similar decentralization trends are visible mostly in Moscow (and to a far lesser extent in St. Petersburg), where the number of private low-rise residential development on the periphery has been growing in the last 15–20 years with the simultaneous formation of peripheral subcenters through private business megaprojects of high-density residential development (Golubchikov and Phelps, 2011).

Other Russian cities, on the contrary, have the development trends that have largely become the reproduction of the Soviet model of urban development. This was expressed inter alia in the maintaining of the *microrayon* type of structure in new urban development projects and the continued high-density development at the outskirts of the cities but with increased average building height. The new development in central parts of the cities largely took the form of infill development while the industrial sites (including abandoned) have attracted little attention from developers. These inertial tendencies towards sprawl emanate from the tenacity of the Soviet period principles of urban development that are engrained in the professional consciousness, in the customary approaches to planning and policymaking, and in the established practice of peripheral green-field development, which is constantly pulling over the limited resources from the central parts of the cities.

The spatial analysis showed that the planning structures of the sample cities have common features inherent in most post-Soviet cities. Despite the general urbanisation trends visible in all the post-Soviet cities, individual peculiarities are also present. In this connection, the next section accounts for the variability among the largest regional centers of Russia presenting the typology of their urban structures.

Typology of the Largest Regional centers

The results of quantifying the sample cities' urban structures have formed the base for the development of their typology. A two-step procedure based on k-means clustering was used for the distribution of the sample cities by type. The four calculated urban form characteristics from Table 1, including shape index, dispersal index, network indirectness index and sprawl index, form a data set for partitioning the 13 observations into k groups.

The first step was to determine the optimal number of clusters, which in the current study was done via the elbow method. The resulting curve is shown in Fig. 4,

[2] What remains common for all the cities in Russia is its specific seasonal suburbanisation expressed in the growth of population in cottage settlements (*dachas*) during spring and summer (Nefedova and Treivish, 2019).

Table 2. Residential density peaks in the sample cities

City	Closest peak	Medium peak		Remote peak
Distance from the city center	5–7 km	9–11 km	15–17 km	20–25 km
Novosibirsk				+
Yekaterinburg	+			
Nizhny Novgorod		+		
Kazan	+			
Chelyabinsk	+	+	+	
Omsk				
Samara		+		
Rostov-on-Don	+			
Ufa	+	+		
Krasnoyarsk	+			
Perm			+	+
Voronezh	+			
Volgograd				

Source: (Koncheva and Zalesskiy, 2016).

indicating the appropriate number of clusters as 2 to 4 (in the location of a bend/elbow). Thus, as a second step, *k*-means analysis was performed for 2, 3 and 4 clusters with the ratio of Between Sum of Squares (BSS) and Total Sum of Squares (TSS), which indicates the goodness of clustering, most closely approaching 100 in the case of 4 clusters. It means, that the observations are to be partitioned into 4 groups. The dendrogram from Fig. 5 produced using hierarchical clustering shows how the regional centers are grouped into 4 clusters and Table 3 summarises the cluster means for all the variables.

Now that the regional centers are grouped into clusters, the types of the spatial structures among the largest regional centers may be identified:

(1) The first type of spatial structure (clusters 1 and 2) with the highest values of the variables' means was designated as "extended." This group of cities is formed by the cities with urban structures featuring the linearly extended shape of the city's area, stretched along the river, with a high degree of development fragmentation—Samara, Ufa, Perm and Volgograd. These cities have a spatial footprint that is significantly larger in the area compared to other cities in the sample and correspondingly high shape index, which in turn results in high values of sprawl index.

Despite the striking deviation of the Volgograd case from other cases, it seemed reasonable to include the city into the "extended" group as an extreme case of almost linear development along the river. In fact, Volgograd has often been cited as virtually the only example of the extended urban structure among major Russian cities: "stripe-shaped" (*polosovidnaya*) structure was attributed to Volgograd by Lappo (1997, p. 37). Whereas the assignment of "extended" type of structure to Volgograd is just apparent and in line with the earlier studies, urban structures of the three other cities that have been distributed to this group by

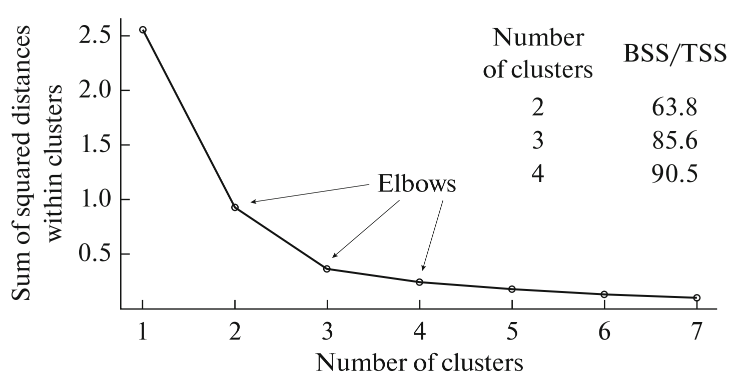

Fig. 4. Elbow method for determining the number of clusters.

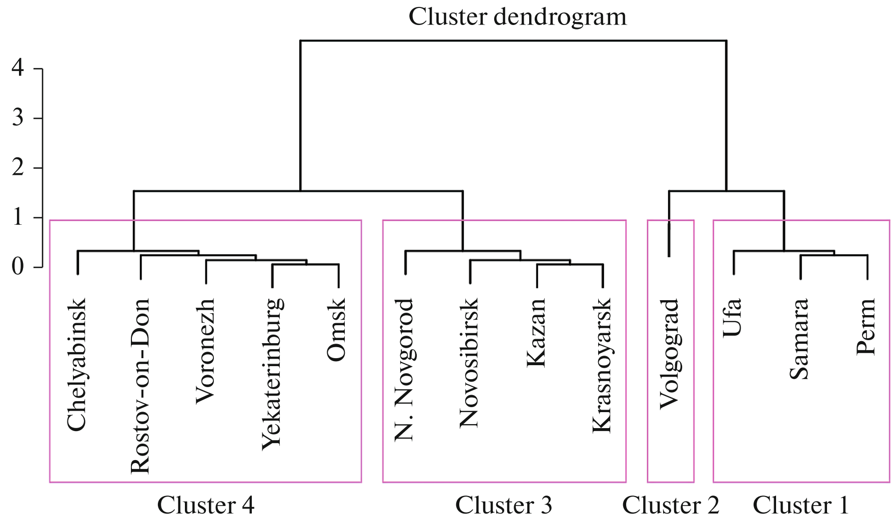

Fig. 5. Cluster Dendrogram with the partitioning of the regional centers into four clusters.

the *k*-means clustering mechanism, have not been univocally marked as "linear" or "extended" before. The urban structure of Perm, for instance, is classified by Lappo as "scattered." While the fragmentation of the Perm's built-up area is undoubtedly one of the key features of its spatial organisation, historically formed due to the difficult terrain conditions and to the peculiarities of the Soviet "leapfrog" model of territorial growth, the "linear extension" tendencies in the Perm's spatial development turn out to be stronger, as shown by statistical modelling. Samara became the most unexpected object in the "extended" group. While its spatial footprint is not obviously extended as in the other cases, the location of its historic center, which functions also as the concentration point for various activities and as the transport center, away from the densely populated neighbourhoods, results in a significantly higher network indirectness and, thus, high sprawl index.

Despite the differences in development paths, Samara, Volgograd, Ufa, and Perm have come to broadly the same type of urban structure, where fragmentation and discreteness,[3] inherent to a varying degree to all post-Soviet cities, are worsened by historically formed linearly extended shape. Such characteristics of urban structure greatly affect the operation of these cities' transportation systems leading to increased length of transport communications and increased level of transport dependency among the population.

Table 3. Cluster means over all the variables

Variable				Cluster assigned
shape	pop_disp	network	sprawl	
1.757	0.677	1.273	1.513	1
2.170	0.880	1.250	2.390	2
1.385	0.768	1.263	1.340	3
1.300	0.672	1.310	1.144	4

Compiled by the author.

(2) The second type (cluster 3) with considerably lower values of the variables' means is formed by the cities with discrete spatial structure featuring built-up areas that are "cut" in two distinct and equally large and important parts by the large rivers—Kazan, Nizhny Novgorod, Novosibirsk, and Krasnoyarsk. Despite the quite compact spatial footprint (low value of shape index), these cities are characterized by the ineffective distribution of population densities across the city's built-up area (high population dispersal index), which results in a moderate level of sprawl index.

The two Siberian cities in the "discrete" group—Krasnoyarsk and Novosibirsk—have been conventionally defined as urban structures consisting of scattered parts both within the academia (Gaikova, 2015) and in the planning documents. The development of Novosibirsk was seen as a complex of three cities with the left-bank and right-bank parts of Novosibirsk initially having independent master plans, whereas in Krasnoyarsk there is a clear division of the old historic part and the Soviet-period "addition" situated on the opposite banks of the river. As regards much more "ancient" Kazan and Nizhny Novgorod, their first

[3] In (Angel et al. 2011) authors define fragmentation as the interpenetration of the built-up areas of cities and the open spaces in and around them, also proposing such synonyms as scattered development or "leapfrogging" development. The spatial structure of "discrete" cities resembles a patchwork with large single-use "patches": densely built residential zones ripped by the large arrays of industrial sites or detached houses/dachas (Gaikova, 2015).

steps towards "discreteness" were made long before the Soviet times: in 1817 in Nizhny Novgorod with the opening of the fair complex on the opposite bank of the Oka River and, a bit later, in 1848 in Kazan with the expanding the boundaries of the city towards Admiralty settlement on the right bank of the Kazanka River and the construction of a dam between the settlement and the city. Yet the much more significant change in the population distribution is due to the Soviet period large-scale housing construction at a considerable distance from the city center.

Being "cut" in two distinct parts by the large rivers, the cities from the "discrete" group are also characterised by the high degree of the built-up area fragmentation despite their significantly more condensed shape and experience the same problems of disconnectedness of the cities' parts as "extended" cities. While the parts of both "discrete" and "extended" cities are often considered as separate settlements in the perception of the population, they cannot really function as self-sufficient urban entities offering the range of possibilities that is comparable with the old center. The sample regional centers are still highly monocentric in terms of jobs location and the strong center attracts most of the population during the daytime, which creates considerable mobility issues.

(3) The third type (cluster 4) with the smallest values of the variables' means is formed by the cities with compact spatial structure featuring a comparatively condensed development and a moderately spread spatial footprint—Yekaterinburg, Chelyabinsk, Omsk, Rostov-on-Don and Voronezh. The smallest value of the sprawl index in this group is ensured by their compact spatial footprint, while the configuration of the street network is not optimal, as indicated by the rather high value of network indirectness.

Despite the designation of 5 out of 13 sample cities into the "compact" group, these cities cannot be considered as compact in the true sense. In fact, Lappo claims that urban compactness is characteristic only of smaller towns (Lappo, 1997). Just as many other Russian cities, during the Soviet period, the regional centers from the "compact" group acquired completely new areas, comparable in size and population to historical cities. In Yekaterinburg and Chelyabinsk, for instance, these came in the form of the 1930s *sotsgoroda* (socialist towns)—the isolated and self-sufficient settlements with well-developed planning structure that are still easily located in the cities' layouts remaining essentially separate cities both in terms of physical connection (transport links) and in terms cultural connection (residents' self-identification and sense of community, etc.).

Yet despite the fragmentation inherent in all the post-Soviet cities, in the "compact" group of cities, the new urban development entities, that appeared during the Soviet period, were located at an acceptable distance, not as far from the existing core as in other cities. Three of the cities in this group do not have large water bodies within their borders cutting the urban fabric and the other two managed to retain the spatial integrity through a network of streets and bridges. All this allowed Yekaterinburg, Chelyabinsk, Omsk, Rostov-on-Don, and Voronezh to remain compact enough for such large cities compared to others in the sample.

CONCLUSIONS

The study has contributed to the understanding of the Russian largest regional centers' spatial organisation assessing their urban structures with a set of quantitative indicators. The GIS-based multivariate analysis was systematically applied to 13 sample cities to identify the main features of their urban form. Delineating of their current built-up areas based on the satellite imagery and land-use maps as well as calculating such measures as general density and dispersion index allowed to situate the spatial structures of the largest regional centers amid the variety of the urban forms that exist in the world. According to these metrics, the spatial structures of the largest Russian regional centers most closely resemble those found in the European cities in terms of density and population dispersion. Nevertheless, the analysis of the population density distribution via the density profiles has shown that the Russian cities have specific traits of the spatial arrangement separating them from the European cities including those with socialist past: the Soviet-period systemic impact of the administrative-command system as a substitute to the market led to the formation of the specific spatial structure with the peripheral density peaks situated at a considerable distance from the city core. This peculiar distribution of population and housing densities across the cities' territories, which is significantly different from the exponential decrease in density from the center to the periphery typical for capitalist cities, is a product of the much more extensive urban expansion of the Soviet period compared with the Central and Eastern European cities coupled with the particular type of suburbanisation described earlier.

The spatial modelling and further calculations of the quantitative metrics served two purposes: it made it possible to identify general patterns in the planning structure of Russia's largest regional centers and formed the base for the development of their urban structures' typology. The sample cities demonstrated essentially the same pattern of spatial organisation characterised by the unreasonably stretched urbanized areas, peculiar density distribution, fragmentation of urban fabric, and resultant ineffective layout of transportation links manifesting in different cities to varying degrees. The typology, produced via the *k*-means statistical clustering technique accounted for specific properties of the regional centers and provided a more systematic view of the spatial organisation of the largest regional centers in Russia. Although sharing some general traits of the "post-Soviet" urban form, five of the sample cities (Yekaterinburg, Chelyabinsk, Omsk, Rostov-on-Don, and Voronezh) demonstrated an acceptable level of territorial and population dispersion and were marked as "compact". Other cities with less efficient spatial structures suffer either from the disunity of their territories separated by large rivers in case of "discrete" cities (Novosibirsk, Kazan, Nizhny Novgorod, and Krasnoyarsk) or from the high degree of development fragmentation and population dispersion in case of "extended" cities (Ufa and Samara, Perm and Volgograd) and should look for the ways to counterbalance their limitations with a well-thought transportation planning contributing to increased accessibility of the attraction points. The assignment of the regional centers to one of the urban structure types makes it possible to better understand the spatial organization of these cities, which, in turn, should serve as the basis for a well-founded strategy for their development in the future.

This study has also highlighted the profound effect of the historical legacies and the urban development tendencies once set and still not overcome. Many of the unique features and inefficiencies of the Soviet development model were inherited by the Russian cities and, in some cases, only strengthened post-1990 despite the transition to a market economy. This phenomenon of the historical persistence of urban development patterns is described in the literature as *path dependency*—a term meaning the ability of initial conditions to influence the paths of development in the future. Gutnov claimed that the fundamental, enduring characteristics of the urban structure that for the first time manifest themselves in the initial, historical plan constitute then a kind of genetic "code" of the spatial organization of the city (Gutnov, 1984). Still, the analysis undertaken has shown that it is the Soviet period, in which the regional centers experienced their most rapid growth, that remains highly influential on their current structure. The initial regular grids of the late 18th–19th centuries that appeared during the rise of neoclassical architecture in Russia, are still very well visible in the central parts of the largest regional centers. But the initial compact urban form has been gradually lost during the 20th century with cities acquiring Soviet industrial and residential belts and joining the surrounding villages.

If the research in this direction is to be continued, the methodology would benefit from several types of improvements and refinements. Firstly, the number of spatial metrics could be somewhat wider to include also job density distribution in addition to population density as well as the spatial arrangement of different land uses. These two indicators probably possess the most explanatory power allowing, inter alia, to properly assess the degree of the cities' monocentricity, which is an important characteristic for determining the strategic direction of development towards either concentration and intensification or, on the contrary, towards a polycentric city with a set of self-sufficient urban entities. While the current evidence suggests that most Russian cities remain highly monocentric (Becker et al., 2012), this proposition needs to be substantiated by proper quantitative analysis. In addition to this, many other spatial indicators that are suggested by the existing studies may support and strengthen the validity of the typological distribution. Yet the choice of the metrics is highly dependent on the data available, while the system of data collection and systematization in Russia is significantly different from what is customary in developed countries. The comparatively scarcity of statistical information is largely the legacy of the Soviet statistical methodology, which, considering the planned economy's specificities and tasks, dealt with a comparatively narrow range of indicators. These specificities will probably force the researchers to look for alternative sources of information other than published by the state and shows some ingenuity in creating synthetic datasets using indirect sources.

Secondly, all the spatial modelling within the study was performed according to administrative boundaries. Since the largest regional centers' agglomerations comprise only small suburbs and rarely secondary cities accommodating the population not exceeding 12 per cent of the total agglomeration population, this simplification has not resulted in any significant distortion of the typology. Yet the good practice would be to consider cities in their physical boundaries, adding the adjacent territories outside the administrative boundary of the city that in fact function as a part of it.

Lastly, expansion of such research both in terms of its geography to cover also medium-sized cities (such metrics may be not valid for smaller cities) and in terms of time will be beneficial for acquiring an even more systematic understanding of the Russian cities' spatial structure. Adding a retrospective angle or continuing to track the same metrics (probably not often than every decade given the rigidity of the urban structures) will allow gaining an insight into the changes the spatial organisation of the Russian cities has undergone and to correlate these changes with the impact of the urban policies pursued by the municipalities.

CONFLICT OF INTEREST

The author declares that she has no conflict of interest.

REFERENCES

Angel, S., Parent, J., Civco, D.L., and Blei A.M., *Making Room for a Planet of Cities*, Cambridge, Lincoln Inst. Land Policy, 2011.

Antonov, E.V. and Makhrova, A.G., Largest urban agglomerations and forms of settlement pattern at the supra-agglomeration level in Russia, *Reg. Res. Russ.*, 2019, vol. 9, pp. 370–382.

Becker, C., Mendelsohn, S.J., and Benderskaya, K., Russian urbanization in the Soviet and post-Soviet eras, Urbanization and emerging population issues working paper 9, Human Settlements Group, International Institute for Environment and Development, 2012.

Bertaud, A. and Malpezzi, S., *The Spatial Distribution of Population in 48 World Cities: Implications for Economies in Transition*, Madison, WI: Center for Urban Land Economics Research, Univ. of Wisconsin, 2003.

Bertaud, A. and Renaud, B., *Cities Without Land Markets: Lessons of The Failed Socialist Experiment*, Washington, DC: World Bank Staff, 1994.

Breheny, M. J., *Sustainable Development and Urban Form*, London: Pion, 1992.

Burgess, E., The growth of the city: An introduction to a research project, in *The City*, Park, R.E., Burgess, E.W., and McKenzie, R., Eds., Chicago: Univ. Chicago Press, 1935, pp. 47–62.

Burton, E., The compact city: Just or just compact? A preliminary analysis, *Urban Stud.*, 2000, vol. 37, no. 11, pp. 1969–2001.

Burton, E., Jenks, M., and Williams, K., *The Compact City: A Sustainable Urban Form?* London: Routledge, 2003.

Choudhary, K., Boori, M.S., and Kupriyanov, A.V., Mapping and evaluating urban density patterns in Moscow, Russia, *Comp. Opt.*, 2017, vol. 41, no. 4, pp. 528–534.

Clark, C., Urban population densities, *J. Royal Stat. Soc. Ser. A (General)*, 1951, vol. 114, no. 4, pp. 490–496.

Clifton, K., Ewing, R., Knaap, G.J., and Song, Y., Quantitative analysis of urban form: A multidisciplinary review. *J. Urbanism*, 2008, vol. 1, no. 1, pp. 17–45.

Deng, J.S., Wang, K., Hong, Y., and Qi, J.G., Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization, *Landscape UrbUrban Plann.*, 2009, vol. 92, nos. 3–4, pp. 187–198.

Dimensions of the Sustainable City, Jenks, M., and Jones, C., Eds., New York: Springer, 2010, 282 p. https://doi.org/10.1007/978-1-4020-8647-2_1

Dokhov, R.A. and Sinitsyn, N.A., Sprawl in Russia: Growth and structural transformation of the Belgorod suburbs, *Reg. Res. Russ.*, 2020, vol. 10, no. 2, pp. 247–259.

Epstein, J., Payne, K., and Kramer, E., Techniques for mapping suburban sprawl, *Photogrammetric Eng. Remote Sens.*, 2002, vol. 68, no. 9, pp. 913–918.

Ewing, R. and Cervero, R., Travel and the built environment: A synthesis, *Transport. Res. Rec*, 2001, vol. 1780, no. 1, pp. 87–114.

Ewing, R., Pendall, R., and Chen, D., *Measuring Sprawl and Its Impact*, Washington, DC: Smart Growth America, 2002a.

Ewing, R., Pendall, R., and Chen, D., Measuring sprawl and its impact, *Transport. Res. Rec*, 2002b, vol. 1831, no. 1, pp. 175–183.

Fleischmann, M., Romice, O., and Porta, S., Measuring urban form: Overcoming terminological inconsistencies for a quantitative and comprehensive morphologic analysis of cities, *Environ. Plann. B.*, 2021, vol. 48, no. 8, pp. 2133–2150.

Frenkel, A. and Ashkenazi, M., Measuring urban sprawl; How can we deal with it? *Environ. Plann. B*, 2008, vol. 35, no. 1, pp. 56–79.

Gaikova, L.V., Polycentrism as a paradigm for the development of Russian cities, *Architechton: Izv. VUzov*, 2015, no. 2 (50), pp. 69–81.

Galster, G., Hanson, R., Ratcliffe, M.R., Wolman, H., Coleman, S., and Freihage, J., Wrestling sprawl to the ground: Defining and measuring an elusive concept, *Hous. Policy Debate*, 2001, vol. 12, no. 4, pp. 681–717.

Golubchikov, O. and Phelps, N.A., The political economy of place at the post-socialist urban periphery: Governing growth on the edge of Moscow, *Trans. Inst.* Br. *Geogr.*, 2011, vol. 36, pp. 3, pp. 425–440.

Guastella, G., Oueslati, W., and Pareglio, S., Patterns of urban spatial expansion in European cities, *Sustainability*, 2019, vol. 11, no. 8, p. 2247.

Guérois, M., and Pumain, D., Built-up encroachment and the urban field: A comparison of forty European cities, *Environ. Plann. A*, 2008, vol. 40, no. 9, pp. 2186–2203.

Gutnov, A., *Evolyutsiya gradostroitel'stva* (The Evolution of Urban Planning), Moscow: Stroyizdat, 1984.

Haaland, C. and van den Bosch C.K., Challenges and strategies for urban green-space planning in cities undergoing densification: A review, *Urban For. Urban Greening,* 2015, vol. 14, no. 4, pp. 760–771. https://doi.org/10.1016/j.ufug.2015.07.009

Harris, C.D. and Ullman, E.L., The nature of cities, *Ann. Am. Acad. Polit. Soc. Sci.*, 1945, vol. 242, no. 1, pp. 7–17.

Herold, M., Goldstein, N.C., and Clarke, K.C., The spatiotemporal form of urban growth: Measurement, analysis and modelling, *Remote Sens. Environ.*, 2003, vol. 86, no. 3, pp. 286–302.

Hoyt, H., *The Structure and Growth of Residential Neighborhoods in American Cities*, Washington, DC: Federal Housing Administration, 1939.

Huang, J., Lu, X.X., and Sellers, J.M., A global comparative analysis of urban form: Applying spatial metrics and remote sensing, *Landscape Urban Plann.*, 2007, vol. 82, no. 4, pp. 184–197.

Inostroza, L., Baur, R., and Csaplovics, E., Urban sprawl and fragmentation in Latin America: A dynamic quantification and characterization of spatial patterns, *J. Environ. Manage.*, 2013, vol. 115, pp. 87–97.

Jaeger, J.A.G., Bertiller, R., Schwick, C., and Kienast, F., Suitability criteria for measures of urban sprawl, *Ecol. Indic.*, 2010, vol. 10, no. 2, pp. 397–406.

Jiang, F., Liu, S., Yuan, H., and Zhang, Q., Measuring urban sprawl in Beijing with geo-spatial indices, *J. Geogr. Sci.*, 2007, vol. 17, no. 4, pp. 469–478.

Kasanko, M., Barredo, J.I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V., and Brezger, A., Are European cities becoming dispersed?: A comparative analysis of 15 European urban areas, *Landscape Urban Plann.*, 2006, vol. 77, nos. 1–2, pp. 111–130.

Kirillov, P.L. and Makhrova, A.G., Current trends in Moscow settlement pattern development: A multiscale approach, *Geogr., Environ. Sustainability*, 2019, vol. 12, no. 4, pp. 6–23.

Koncheva, E. and Zalesskiy, N., spatial development of the largest Russian cities during the post-Soviet period: Orienting towards transit or maintaining Soviet trends, HSE Working Papers WP BRP 04/URB/2016, National Research University Higher School of Economics, 2016.

Kostinskiy, G., Post-socialist cities in flux, in *Handbook of Urban Studies*, Paddison, R., Ed., London: SAGE, 2001, pp. 451–465.

Kovács, Z., Farkas, Z.J., Egedy, T., Kondor, A.C., Szabó, B., Lennert, J., Bakad, D., and Kohánd, B., Urban sprawl and land conversion in post-socialist cities: The case of metropolitan Budapest, *Cities*, 2019, vol. 92, pp. 71–81.

Lappo, G.M., *Geografiya gorodov* (Geography of Cities), Moscow: VLADOS, 1997.

Mahtta, R., Mahendra, A., and Seto, K.C., Building up or spreading out? Typologies of urban growth across 478 cities of 1 million+, *Environ. Res. Lett.*, 2019, vol. 14, no. 12, p. 124077.

Makhrova, A.G. and Babkin, R.A., Methodological approaches to the delimitation of the boundaries of the Moscow agglomeration based on data from mobile network operators, *Reg. Res. Russ.*, 2020, vol. 10, no. 3, pp. 373–380.

McDonald, J.F., Econometric studies of urban population density: A survey, *Econometr. Stud. Urban Popul. Density: A Survey*, 1989, vol. 26, no. 3, pp. 361–385.

Nefedova, T.G. and Treivish, A.I., Urbanization and seasonal deurbanization in modern Russia, *Reg. Res. Russ.*, 2019, vol. 9, no. 1, pp. 1–11.

Patacchini, E., Zenou, Y., Henderson, J.V., and Epple, D., Urban sprawl in Europe, in *Brookings-Wharton Papers on Urban Affairs*, Washington, DC: Brookings Institution Press, 2009, pp. 125–149.

Ptichnikova, G.A., Transformations of the spatial structure of the largest cities of Russia in the post-Soviet period, *Biosfer. Sovmest.: Chel., Reg., Tekhnol.*, 2020, no. 1 (29), pp. 42–56.

Schmidt, S., Fina, S., and Siedentop, S., Post-socialist sprawl: A cross-country comparison. *Eur. Plann. Stud.*, 2015, vol. 23, no. 7, pp. 1357–1380.

Schneider, A and Woodcock, C.E. Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census, *Urban Stud.*, 2008, vol. 45, no. 3, pp. 659–692.

Schwarz, N. Urban form revisited – selecting indicators for characterising European cities, *Landscape Urban Plann.*, 2010, vol. 91, no. 1, pp. 29–47.

Sosnovskiy, V.A. and Rusakova, N.S., *Prikladnyye metody gradostroitel'nykh issledovaniy* (Applied Methods of Urban Studies), Moscow: Arkhitektura–S, 2006.

Sudhira, H.S., Ramachandra, T.V., and Jagadish, K.S., Urban sprawl: Metrics, dynamics and modelling using GIS, *J. Appl. Earth Observ. Geoinf.*, 2004, vol. 5, no. 1, pp. 29–39.

Torrens, P.M. and Alberti, M., Measuring Sprawl (No. 27), Working Paper, London, 2000.

Tsai, Y.H., Quantifying urban form: Compactness versus "sprawl," *Urban Stud.*, 2005, vol. 42, no. 1, pp. 141–161.

Wolff, M., Haase, D., and Haase, A., Compact or spread? A quantitative spatial model of urban areas in Europe since, *PLoS One*, 2018, vol. 13, no. 2, e0192326.

Yakshin, A.M., Govorenkova, T.M., Kogan, M.I., Merkulova, Z.Ye., and Strel'nikov, A.I., *Grafoanaliticheskiy metod v gradostroitel'nykh issledovaniyakh i proyektirovanii* (Graphic-Analytical Method in Urban Planning Research and Design), Moscow: Stroyizdat, 1979.